Aspects of waste materials management in the nuclear industry

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Award date:
2005

Awarding institution:
University of Bath

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A thesis submitted for the degree of Doctor of Philosophy

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March 2005

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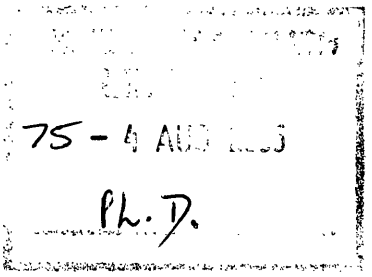
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ABSTRACT

A novel blasting technology (Sponge-jet) used for non-nuclear surface cleaning and preparation has been studied and evaluated for its potential use as a nuclear waste decontamination tool. The technology utilises a polyurethane sponge medium, which is fired at surfaces causing in effect a dry wiping and abrasive action. The process has been considered within the context of being integrated into the overall waste management strategy for the Windscale Active Handling Facilities. The aim has been to provide a waste management system for solid nuclear waste treatment at the Windscale facility that might be made available to the wider nuclear industry. A prototype system has been developed and tested. The results of radioactive trials have been presented and show that the technology could be deployed effectively to successfully decontaminate various classifications of solid nuclear waste. Decontamination factors over 20 have been achieved without generating excessive secondary waste. The recycle-ability of the sponge medium is utilised through the application of a media management system that separates reusable and spent medium from the aerial effluent stream prior to high efficiency particulate filtration and discharge to atmosphere. This has enhanced the process capability of the Sponge-jet technology through enabling potential remote deployment to in-cave situations, and therefore the opportunity to decontaminate more highly radioactive waste such as intermediate level waste. Proposals to manage and dispose of secondary waste medium is also presented, which offer the opportunity to further increase the benefits of waste decontamination using Sponge-jet. The adoption of this technology for nuclear waste decontamination could provide the industry with a useful alternative to other decontamination techniques, which conserves national disposal resources and can be deployed in a safe and environmentally friendly manner.

CONTENTS

NOMENCLATURE

AEAT	AEA Technology plc (separated from UKAEA and privatised in 1996)
ALARA	Concept that radiation doses to the public and the wider environment should be 'As Low As Reasonably Achievable'
ALARP	Concept that radiation doses to the workforce should be 'As Low As Reasonably Practicable' as prescribed in the IRR99.
BATNEEC	Best Available Techniques Not Entailing Excessive Costs
BNFL	British Nuclear Fuels plc
BPEO	Best Practical Environmental Option (choice between widely differing approaches)
BPM	Best Practical Means (optimisation or even best practice for a given option)
BP3	Beta Probe Model 3 (instrument used to measure radioactivity in c.p.s.)
Bq	Bequerel (unit of radioactivity - one disintegration per second)
CAGR	Civil Advanced Gas-cooled Reactor
Ci - MeV	Curie(Ci) - Mega electron Volt(MeV) (radiation energy) a measure of the energy content of radiation
c.p.s.	Count Per Second (measurement of activity as recorded by instrument)
DAC	Derived Air Count, the concentration of radioactivity in air that if inhaled over a year would give rise to a committed effective dose equal to the statutory whole body dose limit.
DEFRA	Department of the Environment, Food and Rural Affairs
DF	Decontamination Factor (a measure of radioactive decontamination reduction)
DPUC	Dose Per Unit Concentration
DP2	Monitoring Probe – Dual Phosphor type 2 probe (used to measure both radiation and radioactivity)
DSC	Differential Scanning Calorimetry
DTI	Department of Trade and Industry
EA	Environment Agency
EA95	Environment Act 1995
EC	European Commission
EDX	Energy Dispersive X-Ray Spectrometry
EIA	Environmental Impact Assessment
EPA90	Environmental Protection Act 1990
FASSET	Framework for Assessing Environmental impacts Project
GWd te^{-1}	Gigawatt days per tonne (time averaged power per unit fuel burned in reactor) a measure of fuel consumption
Gy	Gray, the SI unit of absorbed radiation dose, one joule per kilogram, 1Gy = 100rads
HAWASA74	Health and Safety at Work Act 1974
HEPA	High Efficiency Particulate in Air (filter)
HLW	High Level Waste
HMIP	Her Majesty's Inspectorate of Pollution

HP	Health Physics (a discipline through which radiological protection is established)
HSE	Health and Safety Executive
ICRP	International Commission for Radiological Protection
ILW	Intermediate Level Waste
IRR99	Ionising Radiations Regulations 1999
IRS	Infra-Red Spectroscopy
ISO	International Standards Organisation (e.g., approved freights)
LANL	Los Alamos National Laboratory
LLLW	Low Level Liquid Waste
LLW	Low Level Waste
LoC	Letter of Consent (Nirex)
MBGWS	Miscellaneous Beta Gamma Waste Store (for ILW)
MDI	Methylene Diphenyl-Isocyanate
MoD	Ministry of Defence
MoU	Memoranda of Understanding (e.g., between the NII and the EA)
MSM	Master Slave Manipulator
MW te^{-1}	Mega Watts per tonne (mean power output per unit of fuel - rating) a rate of irradiation
NDA	Nuclear Decommissioning Agency – to be established in April 2005 charged with the responsibility to speed up the decommissioning of the UK nuclear liabilities.
NIA59, 65 &69	Nuclear Installations Acts 1959, 1965 and 1969(amendment)
NII	Nuclear Installations Inspectorate
Nirex	Nuclear Industry Radioactive Waste Executive (body with responsibilities for the development of a national repository)
OSC/COSR	Operational Safety Case/Continued Operational Safety Report
OSPAR	The 'Oslo and Paris' conventions (that led to the Sintra Agreement)
PCSR	Pre-construction Safety Report
PCmSR	Pre-commissioning Safety Report
PMDI	Polymeric Isocyanate
POSR	Pre-operational Safety Report
PPE	Personal Protective Equipment
PRDO	Production Reactor Design Office (the body that was originally responsible for the design of the fuel flask used to transfer elements to and from the WAHFs)
PSR	Preliminary Safety Report
PU	Polyurethane
Qv	Quality Value or factor, of radiation, used to express biological harmfulness of radiation through linear energy transfer.
RCEP	Royal Commission for Environmental Protection
RCF	Rock Characterisation Facility
RF	Release Fraction (proportion of radioactivity that is released from an item for a given event)
RIM	Reaction Injection moulding
RO2	Rate meter used to measure radiation (usually in μ or mSv hr^{-1})
RSA60	Radioactive Substances Act 1960
RSA93	Radioactive Substances Act 1993
RWMAC	Radioactive Waste Management Advisory Committee (advisors to the UK Governement on radioactive waste management issues)

SAC	Special Areas of Conservation
SEM	Scanning Electron Microscope
SEPA	Scottish Environmental Protection Agency
SOLA EO	Substances Of Low Activity Exemption Order
SoS	Secretary of State
SPA	Special Preservation Areas
$Sv\ hr^{-1}$	Sievert(Sv dose rate) per hour (or in sub-units of milli, or micro)
TDI	Toluene Di-Isocyanate
Tg	Glass Transition temperature of a polymer (depending on polymerization and cooling rate)
Tm	Melting Temperature of a polymer (depending on polymerization and cooling rate)
UKAEA	United Kingdom Atomic Energy Authority
UNSCEAR	United Nations Scientific Committee on the Environmental Affects of Radiation.
VLLW	Very Low Level Waste
WAHF	Windscale Active Handling Facilities
α	Alpha (radiation type)
β	Beta (radiation type)
γ	Gamma (radiation type)

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ACKNOWLEDGEMENTS

I would like to extend my appreciation to the following:

1. AEA Technology for their support during this work, and in particular Dr M Stucke who gave me the opportunity to do this work and incorporate it into a course of academic studies.
2. Dr T Mays my supervisor at the University of Bath for his invaluable advice throughout the course of this work.
3. Dr G Neighbour, Mr D Williams and Mr D Broad for the support work they have provided at the University of Bath.
4. Many thanks are extended to colleagues and friends at AEA Technology who supported me while I undertook this work including, Mr and Mrs Hambley, Mr A Brookes, Dr S Ortner and not least all the engineering and industrial staff who have helped in the building and operation of the test rigs.
5. The Environment Agency for providing the necessary support to enable the successful write-up of this work.
6. Last and not least my wife Julie and children who have patiently endured my neglect of them throughout the last six years.

CHAPTER 1 INTRODUCTION

1.0 INTRODUCTION

The circumstances surrounding the management of nuclear waste in the UK have changed substantially over the last ten years, particularly in respect of the disposal of radioactive wastes. A great deal of waste generated by the nuclear industry over the previous four to five decades was stored on nuclear licensed sites within facilities that were never intended for anything more than interim storage pending the arrival of a permanent long term disposal solution. Some wastes had previously been sent to facilities known as silos or ponds, which as they reached capacity closed. These facilities would eventually need to be decommissioned and the waste held removed, and processed ready for further storage elsewhere or ultimate disposal. It was therefore clear that the industry needed new interim storage capacity to store some nuclear wastes until a final disposal route became available. New facilities such as the Miscellaneous Beta Gamma Waste Store (MBGWS) became available at Sellafield with the expectation that a National Nuclear Waste Repository would be available in approximately 2010. A nuclear industry group called Nirex was charged with the responsibility of developing this repository. Its preferred disposal option was encapsulation of appropriately processed wastes within deep underground vaults, at a site near to Sellafield where the vast majority of the nation's nuclear waste inventory is held. As part of the Nirex programme to develop a deep repository for High, Intermediate and some Low Level Wastes (HLW, ILW and LLW), planning permission was sought for a Rock Characterisation Facility (RCF) at Sellafield in order to carry out more detailed investigation of the suitability of the rock for such a repository. However, following a Public Inquiry, planning permission for this RCF was refused in March 1997 [1, 2]. This left the UK with no practical plan for the ultimate disposal of its more radioactive wastes and progress towards a deep repository stalled.

With no prospect of a final disposal route for nuclear waste being available for many decades, and insufficient interim storage capacity, waste issues have now assumed a very high profile.

Increasingly the industry has had to consider more carefully how it generates and manages its waste over recent years. Many areas of the industry use tried and tested means of waste minimisation and are actively seeking alternative means of treating, conditioning and decontaminating wastes to reduce the volumes generated for interim storage. Furthermore increasing pressures on storage facilities will come from the requirement to decommission old radioactive plant where waste volumes will increase dramatically.

The responsibility for the regulation of operations on nuclear sites lies solely with the Health and Safety Executive (HSE) which has delegated its responsibilities to the Nuclear Installations Inspectorate (NII) which issues statutory licensed instruments for practices on nuclear sites. The Licensee has to conduct its operations subject to the conditions of that license in order to maintain safety on site. The NII is responsible for regulating nuclear safety, including the safe management conditioning and storage of radioactive waste on nuclear licensed sites. The operator can only discharge waste from the licensed site in accordance with the limitations and conditions of an authorisation issued by the Environment Agency (EA). The EA is responsible for regulating the discharges and disposals of radioactive waste from nuclear licensed sites to the environment. The NII and EA liaise on issues of mutual concern in accordance with an agreement known as the Memorandum of Understanding (MoU). The objective of the regulators is to maintain and improve standards of protection for the workforce, the public and the environment from the potential hazards from ionising radiation, and to ensure that radioactive wastes are appropriately managed in both the short and long term, in accordance with current legislation, UK Government policy, and other international obligations.

The United Kingdom Atomic Energy Authority (UKAEA) is the licensee for the Windscale nuclear licensed site and responsible for managing the operations at the site, including discharges of waste materials. It manages various tenanted contractors on the site which carry out work such as decommissioning, nuclear research and development and waste processing operations. One contractor is AEA Technology plc (AEAT) which was formerly part of UKAEA prior to its privatisation in 1996. AEAT operates from a number of buildings at the Windscale site and this includes a facility that contains unique shielded cells or caves, known as the Windscale Active Handling Facilities (WAHF). Nuclear Science, a business group within AEAT, runs the WAHF and is developing their waste processing operations. AEAT carries out a great deal of waste processing work for the wider nuclear industry and needs to enhance the performance of this area of its business. The subject of the work that is reported in this thesis involves a potential new approach to specific aspects of waste generation and management at the WAHF. The studies are centred around the decontamination and volume reduction of higher categories of solid radioactive waste to lower levels or even for reuse or recycling (e.g. contaminated tooling).

Over the years a number of initiatives have been carried out to try and improve the management of waste at the WAHF, including the development of specific facilities for wet decontamination, volume reduction, specialised packaging and storage of waste. This made limited improvements in the operations within the WAHF at that time. Changes in the approach to UK nuclear waste management and disposal mentioned earlier have involved new legislation, and tighter controls and limitations on the effluent discharges authorised for the WAHF which have restricted these techniques to small-scale ad hoc

decontamination problems. Volume reduction was only limited to the flattening of thin walled cans and where repackaging would see effective volume savings of approximately 20 to 40%. Compaction of soft materials involved spring back effects or the addition of materials to minimise this effect. The need for a robust larger-scale decontamination and volume reduction process for waste materials was growing, as waste costs were now increasing dramatically.

It was with this background that the WAHF management sought new ideas for developing new waste management approaches. The author had already developed new interim storage facilities for the WAHF and had suggested ways that plastic wastes might be more efficiently managed through heat-treatment. The idea of treating plastics was put on hold due to uncertainties about the behaviour of different plastics and the ability to develop systems to deal with the wide range of plastics that may arise.

In 1996 an engineering business arm of AEAT in the USA developed a commercially available abrasive blasting process used for surface preparation in non-nuclear industries such as the oil industry where anti-corrosive coatings can then be applied. The process had been developed for decontaminating steam generator pipe ends to reduce the radiation levels for welders who connect the new steam generators. This had proved highly successful and immediately raised questions as to whether this could be used to clean contaminated nuclear wastes such that they could be disposed as clean materials or as lower categories of waste. This process was significant because firstly it was a 'dry' process using plastic sponge particulate as the blast medium, and secondly it appeared to present a natural link with the concept of the 'heat treatment' of plastics for volume reduction. The first issue that needed to be addressed was whether the blasting treatment

could effectively decontaminate nuclear wastes, without generating more waste. Secondly could the spent sponge be volume reduced through heat treatment, and thirdly could these techniques be integrated in to a whole process technology that would be economically viable?

In order to develop these conceptual ideas in to a coherent process technology a greater understanding of the Sponge-jet process performance and the materials involved was required. It was at this stage that a part-time industrial academic research degree was proposed. The aims of the work were to assess the processes and plastic materials involved and to understand their behaviour during decontamination and volume reduction. Unique test rigs would need to be developed in order to evaluate process performance and capability, through non-radioactive and radioactive trials. The information collected will be assessed to establish the potential for such an integrated process being adopted at the WAHF and any further work that may be necessary.

1.1 STRUCTURE OF THE THESIS

This thesis is set out as follows. Background issues are discussed in chapter 2. The development and design for each of the initial inactive, LLW and higher radioactivity trial studies are discussed in chapter 3, which includes process or trial rig development where appropriate. The experimental results for each of these areas are described in chapter 4. Methods and results are discussed in chapter 5 in the context of their academic interest and viability in terms of waste management in the nuclear industry, with particular application to the WAHF. Chapter 5 finishes with an indication of opportunities for further work. The thesis ends (chapter 6) with some concluding remarks.

CHAPTER 2 BACKGROUND

2.0 INTRODUCTION

Searches on the internet, the Environment Agency library, University of Bath library, and AEA Technology library databases have failed to discover any studies that have considered a dry blasting process using polyurethane, or any similar polymer based particulate medium for the specific purpose of decontaminating nuclear waste materials on a routine process basis. Also when this work was started no examples were found of any similar techniques being integrated into an overall waste management strategy for decontamination, volume reduction and where possible recycling within the nuclear industry.

The author of this dissertation has been associated with the nuclear industry for over twenty-five years. The first twenty years were spent working at Windscale of which the last ten years have been largely involved in nuclear waste management operations. The author has now moved into a regulatory role with the Environment Agency, and is not aware that this topic has previously received consideration. Private communications have established that this view is shared by others involved both in the use of the process itself and in nuclear waste management [1, 2, 3].

The blasting process itself using the polyurethane media is owned by Sponge-jet Incorporated [(3)] based in the USA, and marketed through their outlets in the UK and Europe. The process was subject to two patent applications in the UK [(4, 5)]. Examination

[1] Private communication in August 1996 with Mr R Davisson, and Mr A Wilks (Sponge-jet Inc.)

[2] Private communications in 1996 with Dr T Mays and Dr G Neighbour (University of Bath)

[3] Private communications in 1996 with Dr H Morgan, Dr M S Stucke, Dr K Butter (AEA Technology plc)

of these applications shows that this process appears to be somewhat unique even for non-nuclear applications. A requirement of such applications is a demonstration that the process is new and not simply adapted from another process. Sponge-jet Inc. have made their own literature searches which refer to the well known blasting techniques such as shot, grit and sand blasting, as well as lesser known surface cleaning and preparation techniques using materials such as CO_2 pellets and wood fibre, or bark. The author is aware of new variants of polyurethane sponge and other plastic medium being developed for use in blasting processes both in nuclear and non-nuclear industries, but there still appears to be no evaluation of their process capability to routinely decontaminating general solid waste from the nuclear industry. The author has considered alternative processes [6 - 13] to Sponge-jet but these have proved to be less promising as an in-cave decontamination process specific to the WAHF. CO_2 pellet blasting while used in particular decontamination problems [6, 7, 8] will be less aggressive than abrasive sponge blasting and will also generate excessive gaseous volumes that may challenge the building ventilation and compromise nuclear containment [6]. Conventional cave cleaning has relied in the past on remote mechanical methods that are limited by the power and reach of the manipulators available. The WAHF is no exception, but this leads to time consuming effort generating large amounts of waste and eventually direct man entry (once dose rates are down to acceptable levels) and consequent radiation dose uptake. Some avenues of decontamination development have explored the potential enhancement of the remote process through the use of light weight rotary brushes [9] deployed by manipulators, but this is still relatively time consuming (brush changing and sweep/hoover up tasks required). Sand and shot blasting, while potentially cost effective in specific situations e.g. concrete decontamination [10], have attendant airborne difficulties, which beside contamination spread, will create visibility problems [11], unless

bulky local ventilation/abatement is employed. Other technologies involving chemicals and liquids are again useful in specific situations, for example the 'Low Oxidation state Metal Ion' process is widely used to clean redundant nuclear plant to 'free release' levels, particularly where closed loop arrangements are involved such as reactor circuits [12]. Apart from the chemicals involved these processes require and generate substantial volumes of liquid, which will require processing. As mentioned previously there is limited capacity for the disposal of radioactive liquid waste at WAHF, so such processes would be difficult to implement there. An alternative plastic blasting technology was considered [13], which involved solid plastic particles being blasted in a similar manner to the Sponge-jet process. A key issue is the mechanics of the process in that the particles recoil in a manner that requires a higher level of containment because dust arising is high.

The recycling and re-moulding of plastics through the application of heat is well known in non-nuclear circles, but its use on radioactively contaminated plastics for volume reduction prior to disposal is somewhat less common. The effect of radiation on plastics generally is well understood and there are many studies on the degradation of specific plastics [14 - 17]. Specific work on some polyurethane materials and their degradation under general radiation has been discussed by Shintani et al [18, 19], revealing work that has shown chain schism and chain extension can co-exist under limited levels of irradiation without any appreciably lowering the molecular mass of the material. This property explains why many polyurethane materials retain their properties and perform well under some of the radiation conditions experienced during nuclear operations. Polyurethane elastomer material has been used extensively at the WAHF as coverings to control the spread of radioactive contamination [20]. Polyurethane material also has a relatively good abrasion resistance [20, 21] which may explain why it has been selected as the polymer

blasting media by Sponge-jet Inc.. The author has found no examples in the literature of heat-treatment, or casting/recasting processes being developed specifically for the volume reduction and waste minimisation of polymers, or more specifically polyurethane waste materials in the nuclear industry.

During the course of this work there has naturally been a need to undertake further searches of the literature in order to develop experimental test rigs, and or adapt the experimental approach. Relevant references and discussion will be made at appropriate points.

The EA authorises all discharges of waste from nuclear licensed sites and the Windscale site is no exception. UKAEA holds the authorisations for the WAHF and is responsible for ensuring that AEA Technology (AEAT) as a tenant and contractor operating in the WAHF comply with the conditions and limits of those authorisations. The authorisations held are for solid ILW and LLW, gaseous discharges to stack, and Low Level Liquid Waste (LLLW). The gaseous discharges are directly to atmosphere [22], the liquid discharges go to BNFL on the adjacent site for further treatment [23], while the solid waste is transferred directly to BNFL for either disposal at Drigg [24] (LLW) or interim storage at the MBGWS [25] (ILW).

AEAT is often contracted to receive solid wastes in to the WAHF from other waste generators such as decommissioning wastes from BNFL. The waste is processed before returning it for disposal or interim storage. AEAT also generates solid wastes arising from the other operations they carry out. These operations aim to manage the waste by

segregating it in to the appropriate waste category (e.g. ILW or LLW), reducing the volume it occupies through compaction and improving the packing density when reloading it to waste containers for disposal or interim storage. Some wastes may need treatment to place them in a passive state e.g. grouting or where the material is highly acidic or alkali, neutralisation. In some cases decontamination can be undertaken to render the waste disposable by another route, but this is limited to relatively small waste volumes where the cost savings can be justified, and where it does not lead to disproportionate discharges via another route or excessive dose uptake to operators.

2.1 WINDSCALE ACTIVE HANDLING FACILITIES

Figure 2.1(a to c) show the layout of the WAHF, which comprise of 13 shielded caves plus ancilliary plant and equipment. Each cave has five workstations equipped with two remotely operated Master Slave Manipulators (MSMs), and a Zinc Bromide (see Figure 2.1c) window. These caves are built from thick reinforced concrete, to provide shielding against radiation produced by the nuclear materials being processed. Handling of fuel (as received) from the reactor stations can generate, for example, oxide and deposit particles, which spall off the fuel and contaminate the insides of the cave facilities. The radiation from this contamination is relatively low compared to the radiation from the fuel itself. Where processes or experiments involve fuel that has breached clad containment (e.g. cutting fuel sections for metallographic examinations), dust from the fuel is spread around the in-cave facilities. This fissile contamination has relatively high radiation levels depending on the irradiation history of that fuel. To safeguard against any spread of this contamination the cave containment relies on a high volume extraction system that ventilates the whole cave facility. The ventilation extract from each cave is via three

stages of High Efficiency Particulate in Air (HEPA) filtration, after which the air is released to a stack via activated carbon beds [26]. Nuclear materials are introduced to the facilities using heavily shielded flasks and can be transferred between the caves along a shielded corridor using a materials transfer system. When equipment and material used in the caves becomes waste it is transferred back out of the facilities via specifically designed and authorised waste routes [22 - 25, 27 - 30]. Figure 3.1d shows the typical flow paths of various waste materials through the WAHF.

FIGURE 2.1a: THE WINDSCALE ACTIVE HANDLING FACILITIES (provided courtesy of AEA Technology plc)

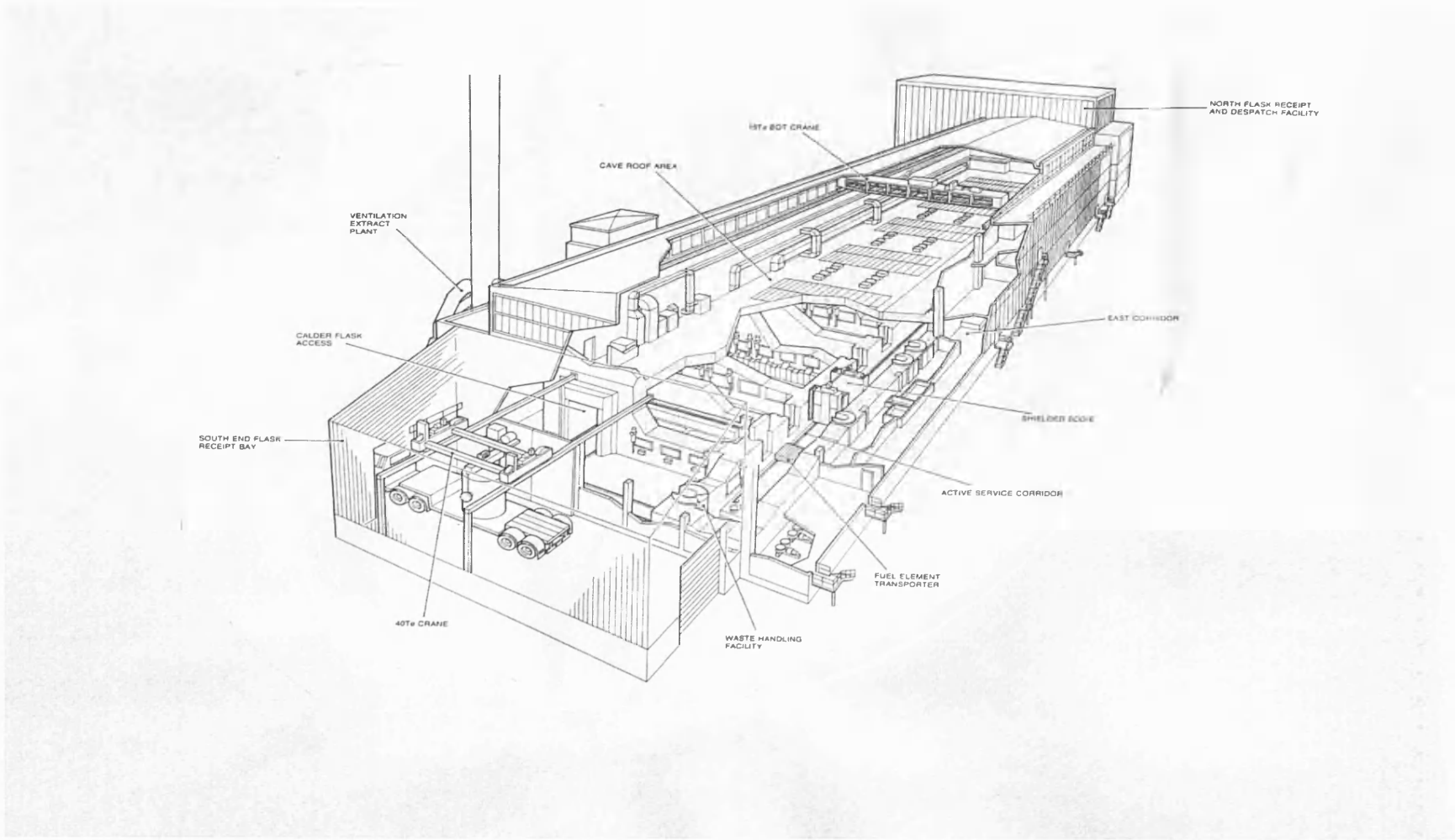


FIGURE 2.1b. PLAN VIEW OF CAVE FACILITIES (provided courtesy of AEA Technology plc)

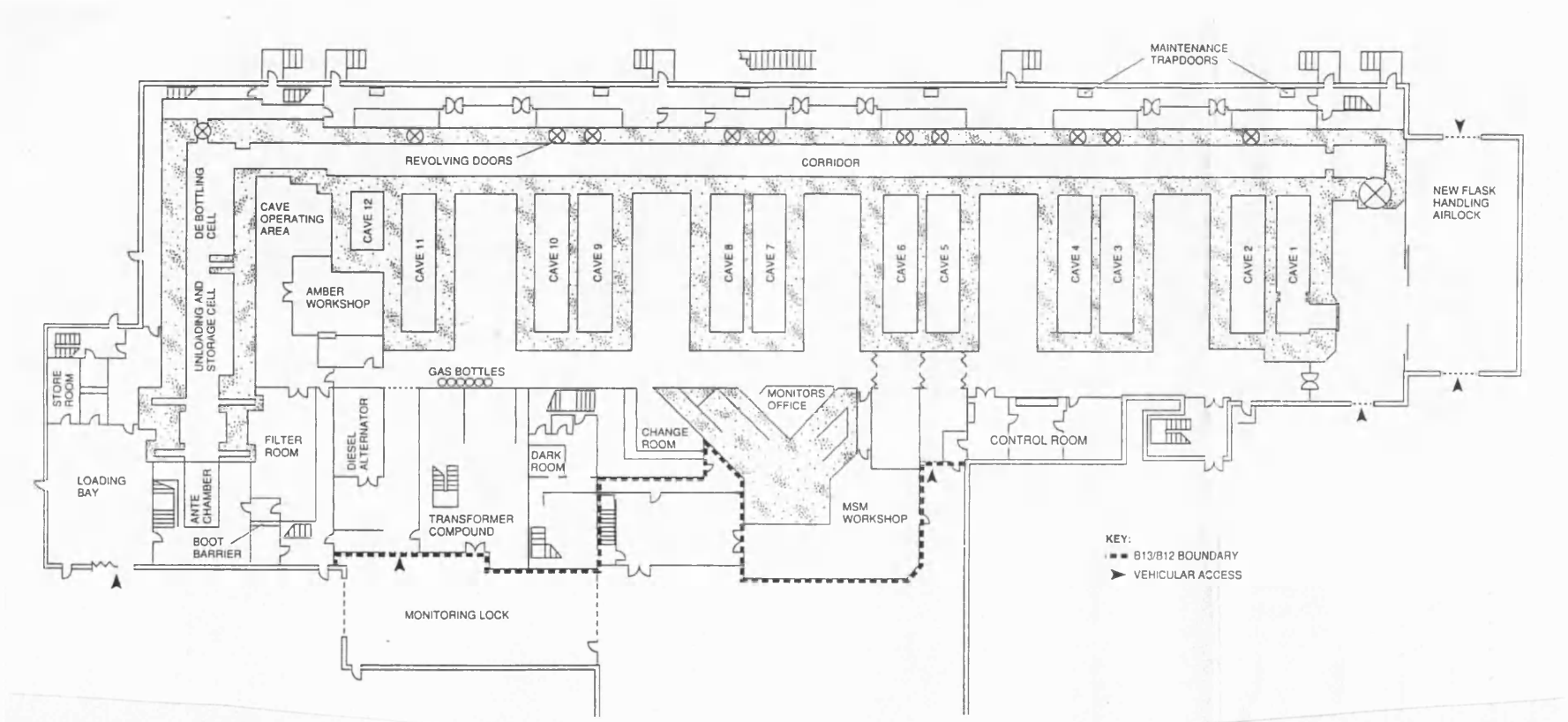


FIGURE 2.1c. VIEWS OF A TYPICAL CAVE (provided courtesy of AEA Technology plc)

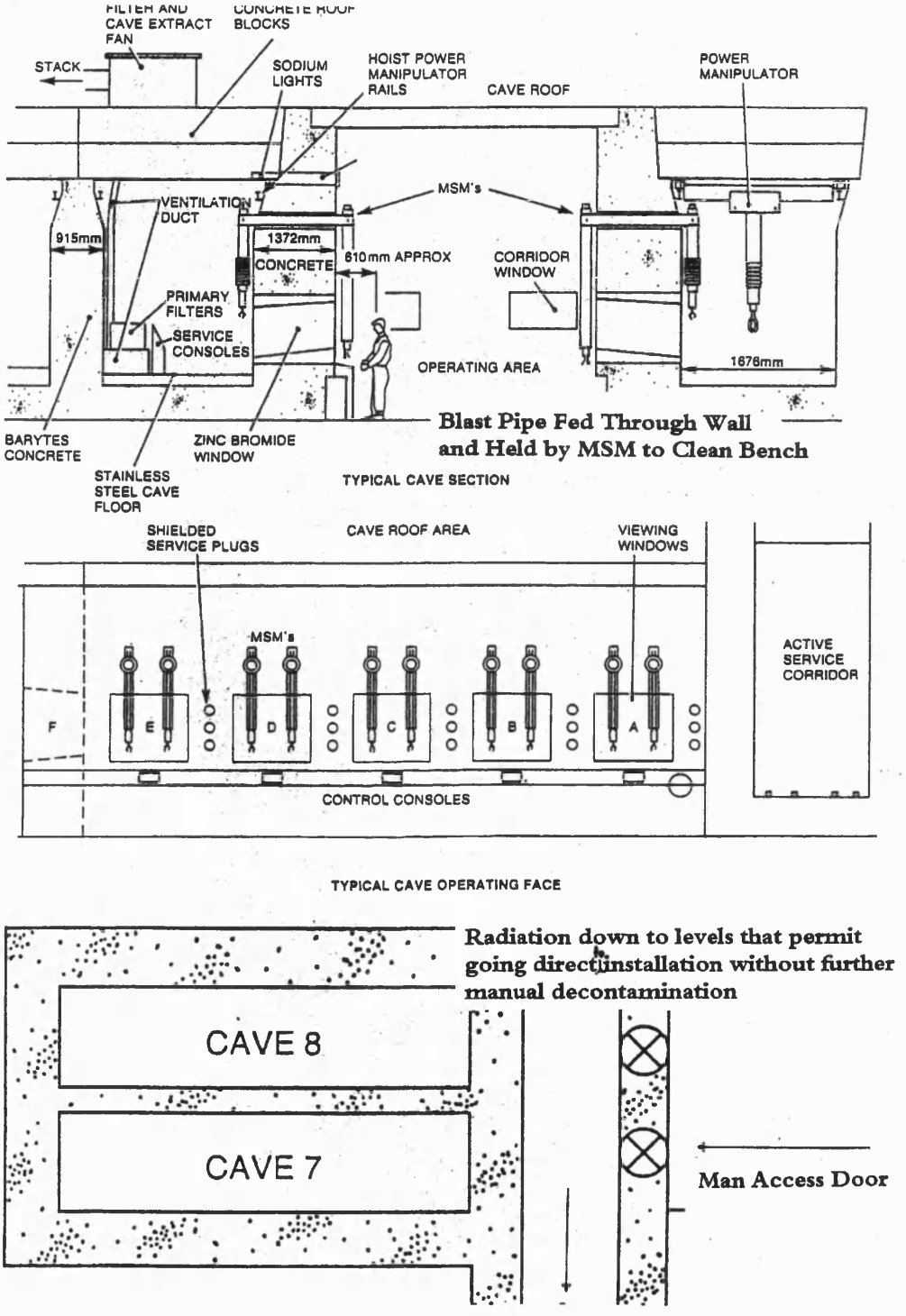
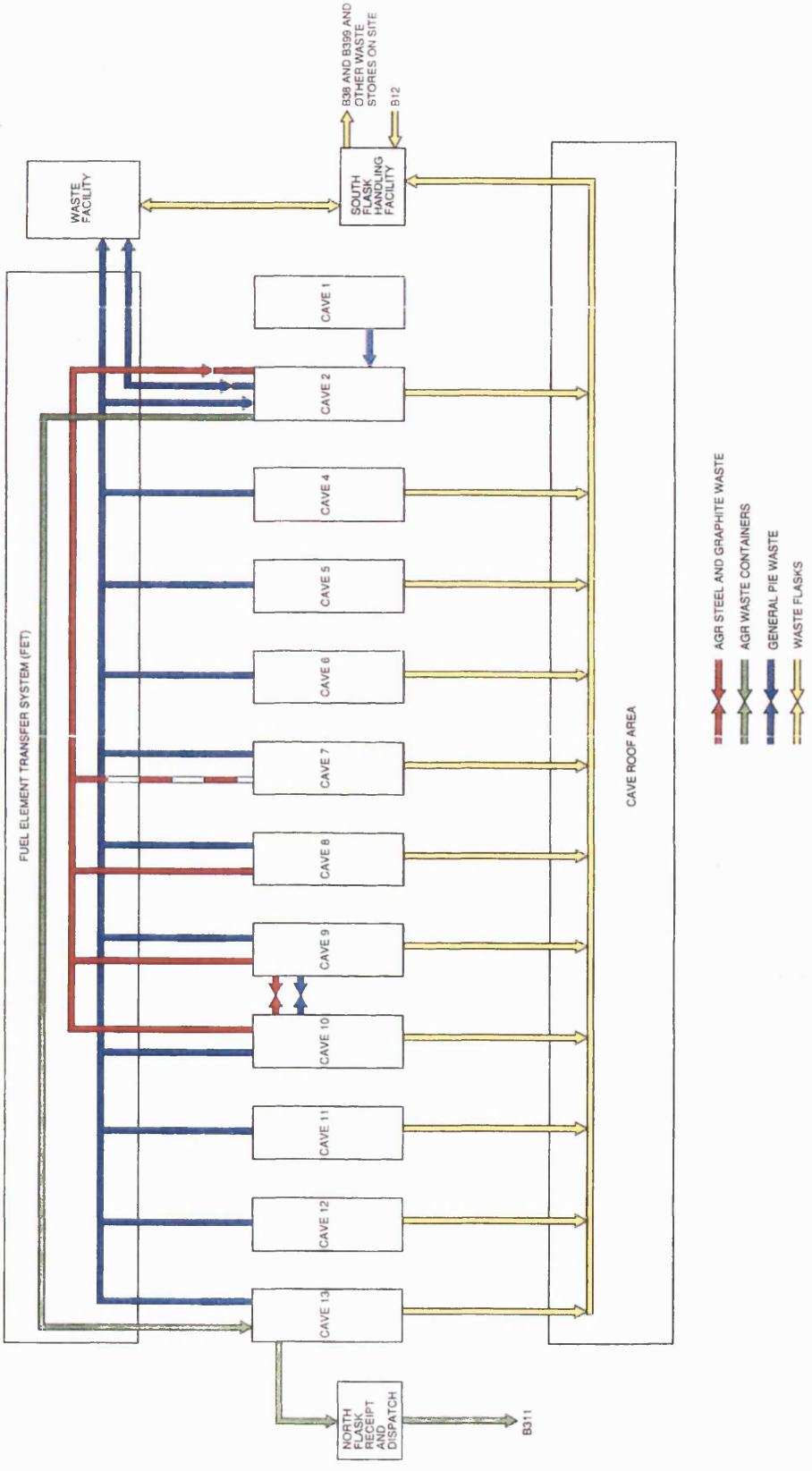


FIGURE 2.1d. SUMMARY OF WASTE ROUTES INTO, THROUGH AND OUT OF THE WAHF (provided courtesy of AEA Technology plc)



2.2 GOVERNMENT POLICY, LEGISLATION AND REGULATION

Nuclear site operators work in a commercial world where profit margins and value for money are important in order to return shareholder investment, but of greater priority are safety and environmental performance in order to satisfy wider stakeholder aspirations. Indeed a failure to meet these latter aspirations could pose the most significant risk to the former shareholder return. In terms of nuclear waste management, operators are required to comply with UK policy and legislation. Historically the Atomic Energy Act 1954 allowed for the authorised waste discharges from UKAEA Sites but this did not apply to non-nuclear sites or to radioactive materials. The increasing use of radioactive materials during the 1950s saw a corresponding increase in radioactive wastes. This led in 1956 to the setting up of an expert group specifically to advise the Government on the control of radioactive wastes, subsequently leading to the White Paper Command 884 [31] – The control of Radioactive Waste, and the Radioactive Substances Act 1960 (RSA 60) [32]. RSA 60 was all encompassing in defining radioactive materials and radioactive wastes, with few if any exemptions. Therefore a review of the uses of radioactive materials and considerations for exemptions was carried out prior to the Act coming into force on the 1st December 1963. Many original Exemption Orders date back to 1962-3, with the purpose of minimising the bureaucracy and regulatory effort likely to be devoted to controlling radioactive materials that had in effect very insignificant impacts on safety and the environment. The 1970s saw the setting up of the Radioactive Waste Management Advisory Committee (RWMAC) following criticism of waste management in the 1976 Sixth Report of the Royal Commission on Environmental Pollution [33], known as the 'Flowers' Report. This led to a White Paper – Nuclear power and the Environment [34]. This placed the responsibility for nuclear waste management policy firmly in the hands of the Secretary of State (SoS) for the Environment, together with the SoSs for Scotland and

Wales. This responsibility would be exercised in close consultation with the Department of Trade and Industry (DTI) and other Ministers with an interest e.g. for defence- MoD. The main elements of these new responsibilities were to:

- ensure that the creation of waste from nuclear activity is minimised,
- ensure that waste management problems are dealt with before any large nuclear programme is undertaken,
- endure that the handling and treatment of wastes is carried out with due regard to environmental considerations,
- ensure the programmed disposal of wastes accumulated at nuclear sites,
- ensure that there is adequate research and development on methods of disposal, and secure the disposal of wastes in appropriate ways, at appropriate times and in appropriate places.

In 1979 a review of the White Paper Command 884 [31] confirmed that the system used to apply RSA 60 was generally satisfactory and no major changes were needed to the legislation.

New statutory powers were introduced in the 1980s where the control and storage of wastes on nuclear licensed sites is still exercised through the site licence enforced by Her Majesty's Nuclear Installations Inspectorate (HMNII).

The White Paper Command 8607 [35] – Radioactive Waste Management, includes an annex, which sets down objectives for radioactive waste management. These were based on the need to justify the practices that give rise to radioactive waste, and that radiation exposures to individuals should be based on recommendations made by the International

Committee for Radiological Protection (ICRP), and shall be As Low As Reasonably Achievable (ALARA).

It was announced that there would be an industry body set up with the purpose of developing an ultimate disposal route for some LLW and ILW radioactive waste, known as the Nuclear Industry Radioactive Waste Executive (Nirex). In 1984 the Department of the Environment produced a national strategy document for radioactive waste management which set out a number of guiding principles which should apply to the interim storage of radioactive wastes, and to the development of new facilities for the ultimate disposal of those same wastes [36].

In 1987 a MoU was signed between the HMNII and the Authorising Departments of Government (the Rimington-Holdgate Agreement, later to become the Slater-Harbison MoU). This agreement has been updated with the creation of the EA in 1996, and the advent of more recent legislation [37]. This accord has been further reinforced by the recent issue of a statement committing the regulators to arrangements for working together in a 'joined-up' way to deliver more effective regulation on nuclear licensed sites [38].

The arrival of the Environmental Protection Act in 1990 [39] required substantial changes to RSA 60, and brought about its consolidation into the Radioactive Substances Act 1993 [40], which came into force on 27th August 1993. A review of radioactive waste management policy was published in 1995 in the White Paper – Command 2919 [41]. This sets out the government policy for the management of radioactive waste in the UK. In the same year the Environment Act 1995 [42] was passed giving statutory powers to the

EA, who then took over the role of regulator for discharges of radioactive wastes from nuclear sites from Her Majesty's Inspectorate of Pollution (HMIP).

Today the responsibility for ensuring nuclear industry compliance with UK policy and legislation with respect to safety and environmental protection in waste management lies with the relevant SoS as applied through the relevant regulators (HSE-NII, and the EA formerly HMIP). The role for regulating discharges of radioactive waste now lies with the EA.

2.2.1 Government Policy

In 1995 the Government carried out the last formal review of radioactive waste management policy in the UK. The results of that review were published in the White Paper of July 1995 [41]. This review was carried out when Nirex had identified a preferred site for a deep repository for ILW and had planned that such a facility would be available by 2010-12 [1]. The Government concluded that deep disposal of ILW was preferable to its indefinite storage and that there was no advantage in delaying the development of a deep repository for ILW. As a result, existing ILW would have to remain in interim storage for at least a further 15-20 years, when transfer to the new repository could be effected. Previous national policy had been that until a waste disposal facility became available, ILW should remain in an untreated form for as long as it was safe to do so, although treatment might be justifiable in order to improve the safety of storage. This reflected the view that some forms of treatment might prove incompatible with the characteristics of a future repository site or design and that treatment could thus effectively foreclose disposal options for the wastes.

The Government expressed its views on this issue of early waste treatment in Paragraph 113 of the White Paper Command 2919 [41] as follows. "The Government believes that where the demands of safety are overriding, ILW must be treated as necessary to improve storage conditions. In addition, where early treatment of waste will secure worthwhile safety benefits, or worthwhile economic benefits without prejudicing safety, the general presumption against action which might foreclose future waste management options may be relaxed. The relevant costs and commercial risks must be borne by the owner of the waste. Decisions by operators and regulators will need to have regard to all relevant factors, including the following:

a) the need for continuing safe storage of the waste, treated and/or contained as necessary;

b) the benefits of placing the waste in a chemically and physically stable form, so that safety may be achieved by passive means;

c) the risk that treated waste will be incompatible with future disposal requirements and the practicability of re-working treated waste in the future, for disposal or for a period of further storage, should this be necessary;

d) the state of storage facilities, including the benefits that would be derived from refurbishment or upgrading;

e) the need to minimise waste degeneration, secondary waste arisings and releases to the environment;

f) the need to minimise dependence on active safety systems, maintenance, monitoring and human intervention;

g) the retrieve-ability of the waste from storage.

As part of its programme to develop a deep repository for ILW and some LLW, Nirex sought planning permission for a RCF at Sellafield in order to carry out more detailed investigation of the suitability of the rock for a repository. However, following a Public Inquiry, planning permission for this RCF was refused in March 1997. With the rejection of this planning application and appeal, the UK was left with no practical plan for the disposal of ILW and progress towards a deep repository was stalled.

Since then, the House of Lords Select Committee on Science and Technology has prepared a report on the management of nuclear waste [43], and the present Government has issued a response [44]. The Government noted the Select Committee's preference for deep disposal of ILW, and agreed that national policy for long-term management of nuclear wastes should be as comprehensive as possible [44]. Various management options for radioactive wastes would be considered, but before coming to a final decision the Government wished to undertake widespread public consultation, with a detailed and wide-ranging consultation paper to be published in 2005-6.

A further development has been the recent publication of the Government's proposed UK National Discharge Strategy [45]. This draft strategy outlines the Government's policy toward meeting the UK's commitments under the Oslo and Paris (OSPAR) and Sintra agreements to reduce discharges of radioactive substances to the marine environment. There are also requirements placed on EU member states through the Habitats Directive [46] to protect rare and sensitive environmental areas (Special Areas of Conservation (SACs), and Special Preservation Areas (SPAs), known as 'Natura 2000' sites) and species. UK legislation (Habitats Regs 1994, Wildlife and Countryside Act 1981 and the

Countryside and Rights of Way Act 2000) implements the requirements of EC directions offering the principle means by which designated conservation sites are protected from the potentially damaging effects of radioactive discharges. The EA has a lead statutory role to regulate discharges from nuclear licensed sites to ensure the requirements of this legislation are met.

2.2.2 Legislative and Regulatory Framework

Implementation of national policy on radioactive waste management and legislative provisions on regulations of radioactive waste management is the responsibility, within the current Government, of the Department of the Environment, Food and Regional Affairs (DEFRA). Both the HSE-NII and the EA carry out regulation of radioactive waste management at licensed nuclear sites. These two regulators, however, have different statutory powers as a result of the variety of legislation introduced during the past 40 years. HSE's statutory powers arise from the Health and Safety at Work etc Act 1974 (HASAWA74) [47] and the Nuclear Installations Acts 1959, 1965 and 1969 (NIA59, NIA65 and NIA69). HSE has delegated its roles under the Nuclear Installations Acts to the NII. The EA's statutory powers are provided for by the Radioactive Substances Act 1993 (RSA 93 formerly RSA60), the Environment Act 1995 (EA95) and the Environmental Protection Act 1990 (EPA90).

The NII is primarily concerned with prevention of accidents and the protection of the workforce and the public, through minimisation of risk and the application of safety assessment principles [48, 49]. The EA is concerned with the effects on the public and the environment arising from any materials discharged from the site as gaseous, liquid or

solid substances (i.e. disposal of wastes, including the deposit and burial of solid radioactive wastes plus routine discharges to rivers, the sea and the atmosphere).

Protection of the public and the environment from the discharge or disposal of radioactive waste is covered by RSA93, which, in the case of nuclear sites, requires authorisation to dispose of radioactive wastes. Responsibility for regulation under RSA93 rests in England and Wales with the EA, in Scotland with the Scottish Environment Protection Agency (SEPA) and in Northern Ireland with the Environment and Heritage Service, an Agency within the Department of the Environment for Northern Ireland.

The operator, NII and EA are increasingly concerned with the conditioning of ILW several years in advance of a final waste disposal route being agreed and many years before it is operational. The waste management route could be to a permanent storage above ground, deep disposal or some other option. Deep disposal would necessitate certain stringent conditions being placed on conditioning but other options might necessitate other conditions. Waste producers are currently taking the view that engineered deep disposal is likely to be the final waste management strategy but they need to be mindful that other options might ultimately be chosen. This means that increasing volumes of waste may need to be treated or conditioned to meet the requirement for safe passive storage on nuclear sites over the next few decades, without necessarily being committed to any particular ultimate disposal route. Also stored waste will need to be protected from containment deterioration or degradation of the waste itself. So there will be increasing pressures on operators and regulators to ensure that the wastes do not pose increased safety risks in terms of both on and offsite impacts, and that

the treatment does not foreclose the use of alternative disposal options and, as such, minimises the need for rework [41]. Also with the increasing pace of decommissioning operations throughout the industry, and the limited storage space available, these problems are likely to exacerbate in the short-term.

The main concern of the EA is to seek to minimise the environmental impact of radioactive waste disposals by ensuring that, where ILW is being conditioned, the packages produced are ultimately suitable for disposal. Safety issues are a major concern and it is important that waste is stored in a safe and suitable manner prior to eventual disposal. Regulation of conditioning and storage of ILW on licensed nuclear sites lies solely with the HSE-NII. However waste producers need to be aware that the NII will not submit consents to the operator or licence applicants until the EA has expressed satisfaction with the radioactive waste management (including radioactive waste disposal) implications. Therefore, a key issue in assessing disposability of waste conditioned early is to determine the degree of deterioration during a prolonged storage period. If deterioration is beyond a certain level, then reworking will probably be required. This may have implications for the subsequent disposal of by-products of any decontamination process e.g. spent sponge medium.

Ultimately the transfer of any such stored wastes to a future disposal facility will require authorisation by the EA (assuming the present regulatory framework still exists), and the EA looks at such applications from a number of perspectives. One area that will be examined is whether the case for treating or conditioning waste can be justified as the best practicable option, known in the industry as the Best Practicable Means (BPM). While

not covered under RSA 93 the approach is similar if not identical to the Best Practicable Environmental Option/Best Available Techniques Not Entailing Excessive Cost (BPEO/BATNEEC) methodologies used in Integrated Pollution Control under EPA 90 for prescribed non-nuclear processes and substances. In determining BATNEEC operators and the EA pay due regard to the BPEO. BPEO was defined in the tenth report [50] of the Royal Commission on Environmental Pollution (RCEP) as: "...the outcome of a systematic consultative and decision making procedure, which emphasises the protection and conservation of the environment across land, air and water. The BPEO procedure establishes for a given set of objectives, the option that provides the most benefit or least damage to the environment as a whole, at acceptable cost, in the long term as well as in the short term." The BPEO/BPM case for nuclear operators justifying a particular waste management strategy would be analogous.

A definition of BPEO is that it involves decisions on waste management being based on an assessment of alternative options evaluated on the basis of factors such as technical performance, occupational and environmental impacts, the cost, and socio-economic implications. BPM could be defined as being where the expenditure is not grossly disproportionate to the benefit produced, and where the provision of materials, plant and equipment, maintenance, operation, supervision and management is optimised as appropriate to minimise the radioactivity, volume and effects of waste being discharged. The key difference between BPEO and BPM is that BPEO compares options that could be radically different, having different impacts on different environmental media. In contrast BPM relates to optimisation within a particular waste management option. A rider to this is that the BPEO is not always BPM, for example certain safety implications

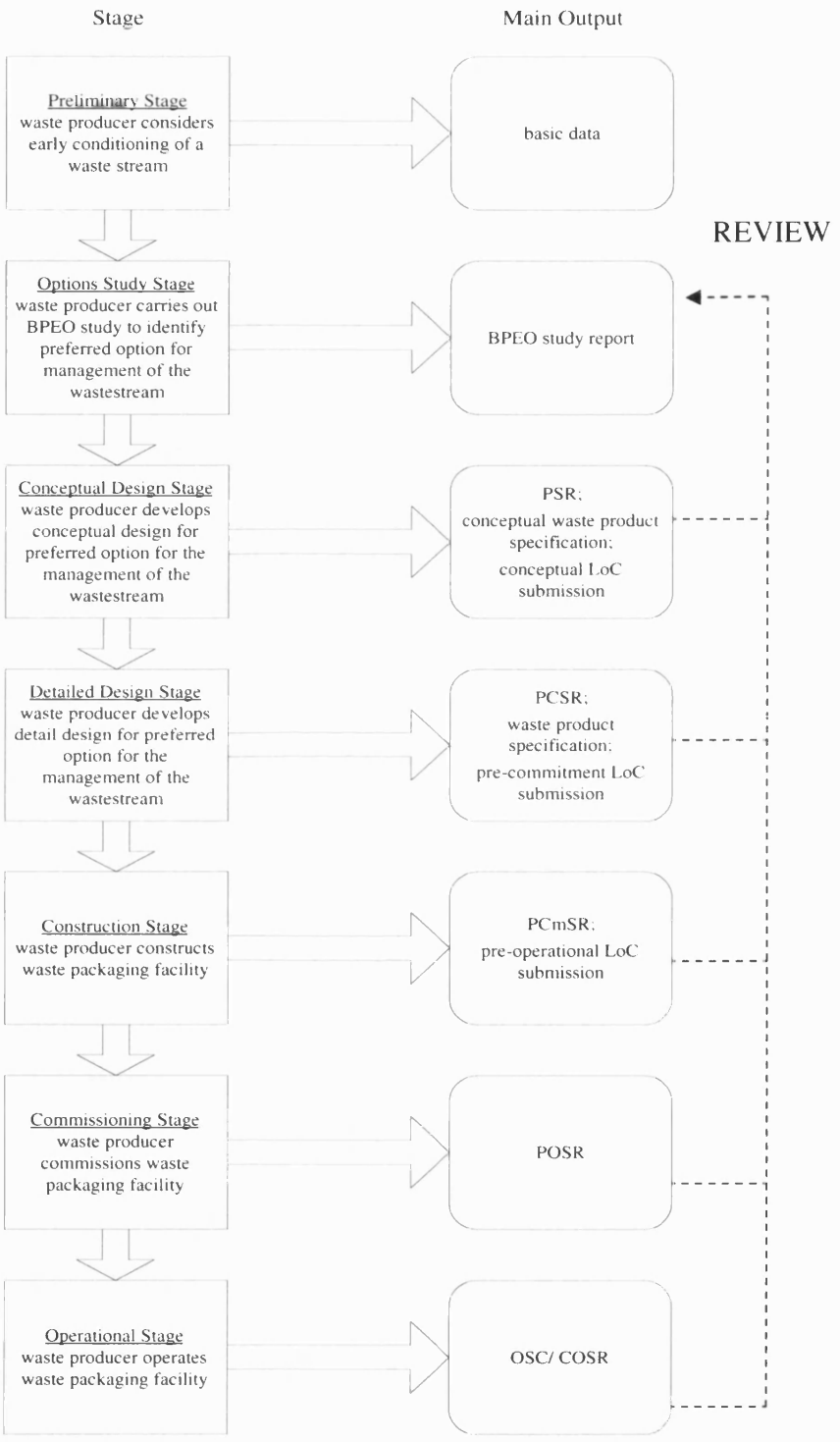
may always take precedence over environmental considerations, possibly making an option untenable. Figure 2.2a describes the key steps in developing any case for a new waste management process. The EA will take in to account the BPEO assessment when determining any application for a radioactive discharge authorisation. Principles that should be addressed in such studies include the need for waste minimisation [41], a downward pressure is maintained on discharges [45], health and safety through radiological assessment [48, 49, 51], protection of communities of non-human species [46, 52], legitimate uses of land and sea should not be compromised and consideration of impacts beyond national border should be assessed. Further to this where there are levels of uncertainty in the study there should be a degree of assessment as to the level of precautionary action required against each option when options are compared.

This regulatory approach goes some way to enable the EA to demonstrate that its statutory duties and the requirements of UK policy and legislation are complied with. Specific policies and legislation toward the Government's proposed UK National Discharge Strategy [45], OSPAR and the Habitats Directive [46] in respect of protecting rare and sensitive environmental areas (SACs and SPAs) and species, has required particular attention. UK legislation (Habitats Regs 1994, Wildlife and Countryside Act 1981 and the Countryside and Rights of Way Act 2000) implements the requirements of EC directions offering the principle means by which designated conservation sites are protected from the potentially damaging effects of radioactive discharges. The EA has a lead statutory role to regulate discharges from nuclear licensed sites to ensure the requirements of this legislation are met. The procedures for protecting humans from ionising radiation are well developed, with systems in place to limit effects on the

individual based on the recommendations of the International Commission for Radiological Protection (ICRP) [51]. This is not the case in terms of establishing the effect of radioactivity on the environment, particularly sensitive habitats and non-human species. An EC funded project is currently under way to develop a framework for assessing the environmental impacts of ionising radiation (FASSET) and is expected to report in October 2003. The EA has a statutory duty to protect the environment and has recognised the need for an interim approach for assessing the impacts of authorised discharges on sensitive habitats. The EA and English Nature have collaborated on a project to review current knowledge on the exposure and effects of ionising radiation on wildlife and develop approaches for protecting the environment [52]. This enables the EA to meet its statutory obligations pending the arrival of formal guidance from the EU project.

Any new application to process waste via a new decontamination and volume reduction strategy generating new waste streams will need to be able to demonstrate the BPEO/BPM case, which will need to include due consideration of impacts on sensitive

FIGURE 2.2a. SUMMARY OF KEY WASTE MANAGEMENT STAGES WITH MAIN OUTPUTS



wildlife, in order to have any prospect of being authorised. This needs to be integrated into the many processes/approaches to managing the conventional safety that is already operating on nuclear licensed sites [53]. Figure 2.2a suggests how this might be depicted for a new nuclear waste management process.

2.3 THE SPONGE-JET BLASTING PROCESS

This system of blasting is a relatively recent innovation used originally for the surface treatment of materials in the non-nuclear industry (ie. at off-shore installations). In the last few years sponge blasting has been applied in the nuclear industry to a limited number of applications associated with dose minimisation during maintenance or decommissioning work. This project is aimed specifically at adapting this process for nuclear waste processing within a cave at the WAHF.

The supplier provides a blasting machine that operates using a compressed air supply (no electric supplies are needed). This machine can be loaded with a charge of sponge particles, which are then delivered in a controlled manner to a high-pressure airline from which they are blasted at high velocity out through a nozzle. Altering the blasting system parameters using its onboard control system can control the velocity and rate of discharge of particulate. The nozzle could be manually directed at the surface to be treated or it could be automatically or remotely controlled, given that the process is suitably adapted.

The supplier also provides a range of sponge particulate media made from polyurethane foam. The foam or sponge particles effect a high pressure wiping action on impact with the object being treated. This is essentially a non-abrasive treatment, although by altering the method of manufacture sponge particles of varying density can be supplied, which can clean softer materials causing less damage. Also various abrasive grit additives can be included during manufacture that produces particulate media with abrasive grit embedded, that will remove base material from the surface of the object being treated as well as providing the same wiping action.

The supplier also provides recycling equipment in the form of a pair of grading sieves (which are also pneumatically operated). This enables operators to take advantage of the reusability or recycle-ability of the medium. The supplier claims that the medium can be recycled up to ten times before it is spent. This attribute could prove crucial in determining whether the process will be economical in decontaminating nuclear waste.

The supplier of the sponge blasting technique claims a particular advantage over conventional blasting processes in that it generates much less airborne particulate. This and other promotional claims for the sponge process must be verified within a radioactive environment. Little or no hard data exists on this subject; these studies intend to remedy this situation.

The process has been used to reduce operator radiation dose levels by removing or reducing the radioactive contaminants that give rise to the radiation [54]. It is therefore

known that the process can remove contamination, but the decontamination performance will need to be quantified more closely, and the processed developed for remote operation before it can be used as a routine waste management tool.

2.4 POLYURETHANE

It is well known that many thermoplastics are moulded at temperatures within their softening temperature range and made into various products [14, 55]. At the WAHF a large number of polyurethane (PU) MSM gaiters [20] [4] are used to protect the manipulator mechanisms (see Figure 4.1j) from contamination thus minimising radiation dose uptake to maintenance workers during repair operations. The Sponge-jet medium used in the blasting process for decontamination is also made from PU [56, 57]. These PU items, along with many other plastic materials, constitute a relatively large volume of waste material generated by operations at the WAHFs; any method to minimise this waste would be welcomed. The approach of using heating above the materials Tg and into the softening range of temperature to reduce the volume of the used waste PU materials has been promoted as a possible 'environmentally friendly' waste minimisation technique for use in the WAHF at Windscale. Communications with the supplier confirm that there should be no evolved gases in these temperature ranges [4]. Other techniques such as compaction tend to spread contamination around the cave environment leading subsequent sources of radiation dose during clean up adding to the overall costs of such work. There are many different types of polymer and they all behave differently when heated. Therefore in order to establish the viability of the technique it was considered appropriate to conduct trials

[4] Private communications in 1996 with Leslie Beddow and Alex Kean (Beakbane Ltd) and John McEroy (AEA Technology plc) confirming the potential to heat treat polyurethane for volume reduction.

initially on PU gaiter material and the PU sponge medium arising from the Sponge-jet decontamination process trials.

At the start of this project there was a volume of ~1 m^3 of contaminated MSM gaiters held in the WAHF awaiting transfer for interim storage at the MBGWS, with further waste gaiters arising as MSMs are maintained (see Figure 4.1j). This waste problem coupled with potential spent PU medium from the Sponge-jet decontamination technique has raised the possibility developing a novel approach to waste minimisation.

The success of volume reducing PU material could significantly affect the viability of the overall waste management strategy using the sponge blasting process as a decontamination tool. It is also possible that the technique could be applied to other plastic or polymeric materials generated as contaminated radioactive waste through out the industry.

2.4.1 Polyurethane History

Polyurethanes were first invented in 1937 by Otto Bayer who discovered the polymerisation reaction between various diisocyanates and hydroxyl compounds, although similar reactions were known as far back as the mid-1800s [21, 58]. This polymerisation process essentially produces addition polymers that fall in to three broad groups; flexible foam, rigid foam, and elastomers. During the 1940s and 50s there were a number of significant developments in the manufacture of PU from elastomers, coatings and adhesives to flexible and rigid foams. Most polyurethanes today are produced from toluene di-isocyanates (TDI) or methylenediphenyl di-isocyanates (MDI) and either polyester or polyether based polyols. There is a wide range of PU material available

which reflects the flexibility with which the component compounds can be altered to meet the service requirements of the finished product.

The MSM gaiter PU material is an elastomer made from MDI and a polyether or polyester macroglycol [20], while the sponge media is made from TDI and a polyether based polyol, blown using water to generate a CO_2 gas in forming the open celled foam structure [5] [5]. There are also specific chemical additives that give these materials some of their properties, but this is strictly proprietary information. The behaviour of these PU materials under re-heating needs to be characterised, particularly after exposure to radiation. Radiation can cause simultaneous cross linking, chain scission and reconnection of broken chains within the PU microstructure [14 - 19]; the levels of each vary depending on the level of damage inflicted by the radiation and whether the PU is chain extended. At higher radiation levels it is highly likely that chain schism will be the dominant effect on PU changing many of its physical properties. In order to develop a successful waste minimisation process for the WAHF the effect of radiation damage on the PU properties will need to be studied in case it influences the effects of any heat treatment process, and this will form an essential part of this research project.

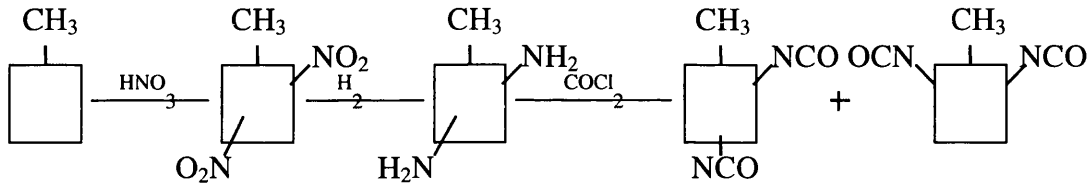
2.4.2 Polyurethane Chemistry

Polyurethane is an important addition polymer ranging in form from soft linear thermoplastic elastomers to hard thermoset rigid foams, and is readily produced from liquid monomers. The basic compounds used to make polyurethane are poly or diisocyanates and macroglycols or polyols.

[5] Private communications in Oct 1998 with Mr C Stone (Director Sponge-jet Inc, USA) on the make-up and method of manufacture of the sponge media.

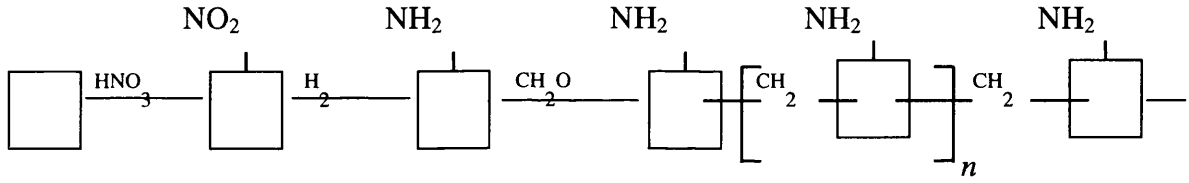
The two commonly used isocyanates are TDI and MDI mixtures made by phosgenating polyamines. The reactions used to produce commercial isocyanates can be summarized as follows;

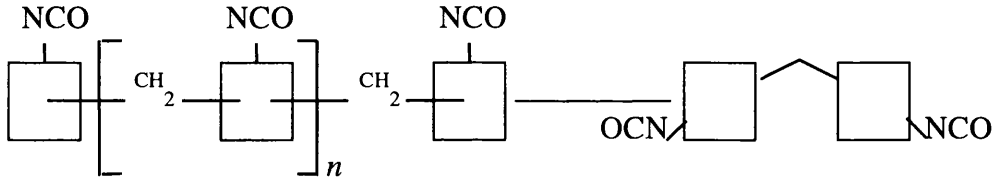
TDI



TDI

MDI





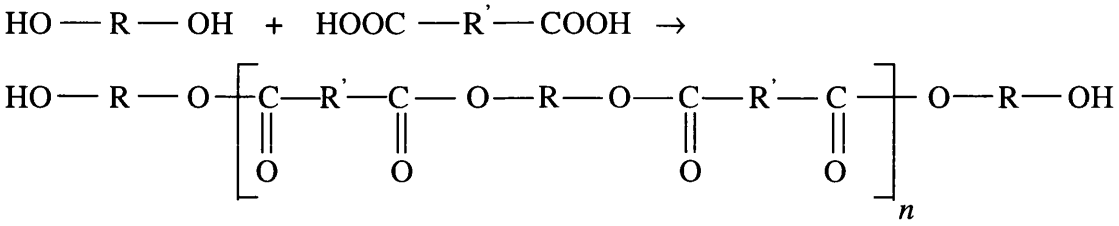
PMDI MDI

Note that MDI and Polymeric Methylene Diphenyl-Isocyanate (PMDI) are coproducts and separation is achieved by distillation of the reaction mixture.

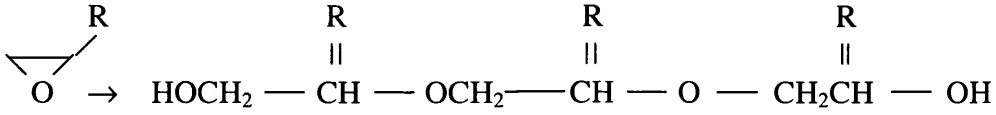
Macroglycols or polyols are used as co-reagents in the production of PU and can be polyester or polyether based. Polyether based polyols are lower molecular weight

polymers and are more commonly used in PU manufacture. The reactions used to make these polyols can be summarised as follows;

Polyesters

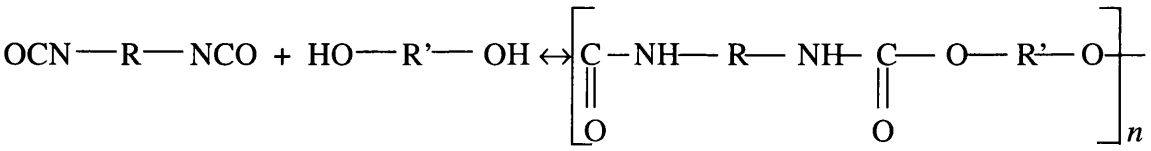


Polyethers



A polyol can also be made from polymerisation of caprolactone.

These two compounds are then combined with various catalysts, and other additives to produce a polyurethane (foams require the addition of a blowing agent) with the required properties for service. This reaction can be summarised as follows;



2.4.3 Polyurethane Manufacture

Polyurethane can exist in many forms and chemists employ different variations in the basic chemical reaction for each PU material type. Manufacturing is more straight forward in that the chemicals can be mixed in one or two stages and either cast (continuous slab or pour in-situ), formed to make thin films (e.g. calandering [59]) or pressure/injection moulded (e.g. compression/reaction injection moulding (RIM) for thermoset PU to make automotive parts).

The one or single stage process involves combining the polyisocyanates, polyols and additives in one mixing tank at the same time. This is known as the 'one-shot' process. The two-stage process is known as the 'prepolymer' process, where the polyisocyanate and polyol are mixed together first to form a polyol or polyisocyanate polymer (depending on the ratio). The polymer is then mixed in a separate mixing tank with the additives after which it is then poured or rolled out in a continuous slab or sheet application. The latter technique is clearly going to be more costly, and therefore explains why most PU production employs the one-shot approach.

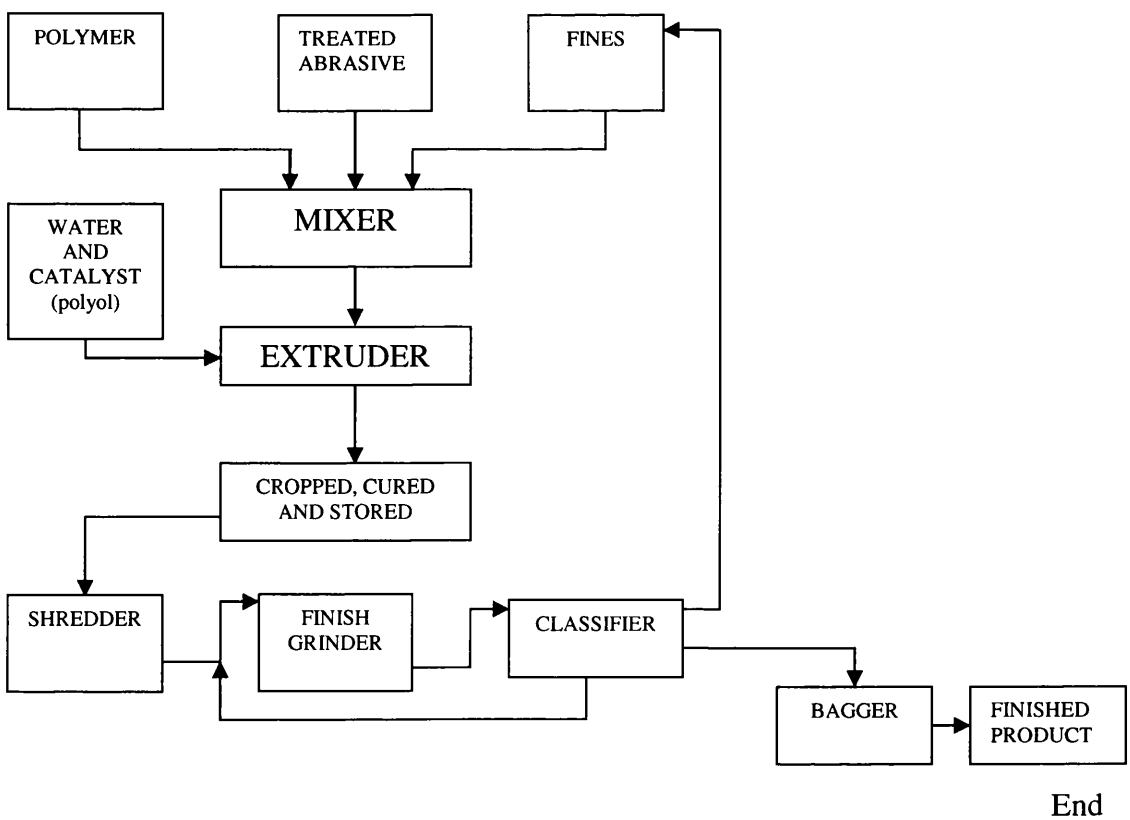
MSM Gaiters

The PU gaiter materials are linear thermoplastic elastomers that are manufactured in two ways since the corrugated parts are clearly moulded to form the shapes, while the film or sheet is probably poured and rolled [58, 59, 60]. Subsequently the parts are fabricated together using heat welding techniques.

Blasting Media

This media is a thermoset PU foam that has been produced using the prepolymer technique [56 - 59]. This method of manufacture has been chosen to ensure the fairly uniform distribution of a key additive, the abrasive particulate, throughout the media providing consistency of performance when in service. The final mix is continuously poured as a slab on to moving release surface, where after initial curing it is chopped into short lengths and stored until fully cured. These lengths of slab stock are then processed through milling machine that chops up the foam slabs into particles up to roughly 1cm across. The particulate medium is finally sieved to remove oversize particles, dust and very small pieces of PU which are then recycled back to the reaction mix for the next batch of medium [5]. Figure 2.4a describes this process.

FIGURE 2.4a. SPONGE MEDIA MANUFACTURING ROUTE



2.5 RADIATION AND CONTAMINATION

All nuclear operators who work with radioactivity are bound by the Health and Safety at Work Act 1974 [47], and are required to adhere to the Ionising Radiation Regulations 1999 (IRR99) [62]. These regulations require the operator to take the necessary steps to restrict exposure to employees and other persons (including trainees, contractors and other members of the public) from ionising radiation. The employer is required to restrict radiation exposure or dose uptake to employees or other individuals in the work place to levels that are As Low As Reasonably Practicable (ALARP). This must be achieved by means of engineered controls and design features, the use of safety features and warning devices, and systems of working that could provide for shielding from radiation, ventilation to minimise airborne radioactivity, containment of radioactive materials or waste substances and minimisation of contamination spread. The annual whole body dose limits, or effective dose equivalent from external radiation plus the committed effective dose equivalent from that year's intake of radionuclides is 20 mSv per calendar year for employees older than 18 years of age (although this may be exceeded for individual years up to 50 mSv in special extenuating circumstances, but even then not to exceed 100 mSv over a 5 year period), and 6 mSv for trainees. All other persons (including the public) must not exceed 1 mSv per year. The area of worker dose uptake under the IRRs is regulated by the NII.

In managing radioactive waste, operators and regulators alike also need to be mindful of potential radiation exposure to individual members of the public, and collective dose to

the population as a whole. These exposures need to be ALARA, economic and social factors being taken into account [50]. The ICRP recommended that the effective dose equivalent from all sources, excluding natural background radiation and medical procedures, to representative members of a critical group of people [51] should not exceed 1 mSv in any one year; however in the event of accident situations at nuclear sites emergency plans and countermeasures are considered where offsite impacts may give rise to a public dose of 5 mSv. There are also limits on the collective doses that a population may receive. These objectives were also stated in the Government's White Paper Command 9852 [44]. There are also other lower objectives used by the operators and regulators in assessing and planning work operations (including waste management operations), known as dose constraints which aim to limit potential dose to individual and populations from specific individual sources and groups of sources on nuclear sites.

The source of this human dose uptake can arise from exposure to direct radiation known as external exposure, or internal exposure due to the intake through inhalation or ingestion of radioactive contaminants or materials from nuclear operations. These materials may have been formed as a by-product of nuclear fission (i.e. fission products in spent fuel through interaction with neutrons), or the material's atomic structure has been activated through irradiation (i.e. activation products in fuel cladding, other reactor core materials through interaction with ionising radiation), and materials that have come in to contact with fission/activation products to become what is termed 'contaminated'. These materials are effectively unstable (i.e. radioactive) forms of elements known as radionuclides, in that they contain atoms made up of particular combinations of protons and neutrons. All atoms of an element contain the same number of protons, but may have different numbers of neutrons and therefore possess a different mass number. These are

known as isotopes of a particular element, and if radioactive are called radioisotopes. Some elements can occur in several isotopic forms e.g. ^{58}Co, and ^{60}Co, as well as in their stable form ^{59}Co. These radionuclides can emit various types of radiation (depending on the isotope) during their life cycle. This period is measured by what is termed their half-life, where they are said to decay over this period to half the radioactivity they possessed at their start in life. Nuclear radiation can take the form of alpha (α), beta (β) or gamma (γ). Rutherford [63] first discovered that several forms of radiation exist, when he found that some radiation could only pass through a few centimetres of air while other types of radiation could travel through up to hundreds of times that distance in air. He concluded that there must be at least two forms of radiation and called the former α radiation and the latter β radiation. Later a much more penetrating radiation called γ radiation was discovered by Villard [64]. Alpha and beta radiation both consist of charged particles that can be deflected by electric or magnetic fields. Gamma radiation consists of electro-magnetic radiation of extremely short wavelength (10^{-14} to 10^{-10} m), and is much more penetrating than X-ray radiation (wavelength 10^{-9} to 10^{-11} m), and can not be deflected by electric or magnetic fields. Beta radiation consists of electrons emitted with considerable energies from atomic nuclei while alpha radiation consists of much heavier particles formed by two protons and two neutrons bound together in the nucleus and ejected as a single stable mass. The alpha particle has the same structure as the nucleus of the helium atom ($^4_2$He).

As the radioisotopes decay these radiations will be emitted and the isotope transforms to another radioisotope, known as 'daughters'. When the atomic mass changes a new isotope of the same element is formed, and when the atomic number changes a new nuclide is formed. So as the radionuclide decays it transforms in to a new radionuclide.

If the radionuclide emits an alpha particle it will change to the radionuclide of another element.

$$\frac{a}{z}X \rightarrow \frac{a-4}{z-2}Y + \alpha + 8MeV \qquad \text{.....(2.5.1)}$$

Where a is the atomic mass, z is the atomic number, X is the 'parent' radionuclide and Y is the 'daughter' nuclide. This means that 8 MeV is released as energy during the decay (8 x 1.6 x 10^{-13} J), and will be shared as kinetic energy between the daughter radionuclide and the alpha particle. If the radionuclide decays by beta emission (β) an electron will be released from the nucleus resulting in an increase in atomic number and a decrease in neutron number, with the mass number staying constant.

$$\frac{a}{z}X \rightarrow \frac{a}{z+1}Y + \beta^{-} + 0.1MeV \qquad \text{.....(2.5.2)}$$

Again the energy released during decay albeit much less, will be shared between the smaller beta particle and the daughter radionuclide. Daughter nuclei formed during radioactive decay often have more energy than is necessary for stability. This energy is emitted as a photon, a pulse of electro-magnetic radiation called gamma radiation. The fundamental law of radioactive decay can be described as the number of nuclei (ΔN) which decay in time (Δt) is proportional to both the length of the time interval and the number of nuclei in the sample:

$$\Delta N = -\lambda N \, \Delta t \qquad \text{.....(2.5.3)}$$

where λ is the positive disintegration constant. In differential form, the negative sign accounts for negative ΔN, and positive Δt, this gives rise to the fundamental law of radioactive decay:

$$\frac{dN}{dt} = -\lambda N \qquad \text{.....(2.5.4)}$$

where the rate at which radionuclei decay is known as the activity of the sample. So the radioactivity of a given sample of a particular radionuclide is proportional to the number of nuclei in the sample. The disintegration constant λ varies from one radionuclide to another. As these radiations are emitted the radioisotope will decay and transform to the daughter radionuclide. This series of transformations is known as the decay chain or series. Each radioisotope decays at a steady rate and always decays down the same series of new isotopes and nuclides, eventually forming as a more stable material (e.g. Thorium 232 (^{232}Th) will decay eventually to Lead 208 (^{208}Pb)). Each radioisotope's half-life is the average time interval required for half the nuclei in a given mass of that particular radioisotope to decay or disintegrate.

The decay of radioactivity in a given mass will give rise to some emissions being absorbed within the radioactive mass. Only a fraction of the radiations released during decay actually escape from the mass. Furthermore, any monitoring probe nearby will detect only a fraction of the radiation released. It therefore follows that the count rate of any detector is proportional to radioactivity but far from equal to it.

The main types of radiation of interest in this study are beta (β - particles), and gamma (γ - rays). Also for the purposes of this decontamination process it is only applicable to surface contaminated waste, it would be impractical to decontaminate materials that are intrinsically radioactive (e.g. activated steel from reactor cores) or contaminated throughout the material matrix (e.g. concrete with permeated caesium contamination). Therefore monitoring detectors will account for more of the radioactivity present in a surface contamination situation. Various radioactivity measuring equipment will be used during these trials. Clearly accurate measurements of dose rates will be required to

ensure a reasonable level of precision in the determination of radioactivity, some measurements/calculations will be in counts per second or minute. For example some contamination is loose on the surface of waste material while some is fixed. A measure of loose contamination present is the activity removed by a swab sample. Here a filter paper wipes a known surface area and the paper is put into shielded chamber with a Geiger counter installed. The Geiger counter is a device counting individual disintegrations from the radioactive contaminants present. It consists of a glass tube filled with a gas (e.g. neon, chlorine and some argon), with an anode fitted within the one end and running the axis of the tube and a foil or mica window at the other end. A cathode is fitted in series with resistance of several MΩ, and a potential difference of a few hundred volts. As the Geiger counter stands there is no current flowing and the potential difference across the resistor is zero. If radiation enters the tube it will ionise the gas and a current will start to flow through the tube. The potential difference across the resistor rises with this current, and a sharp pulse is transmitted through a capacitor to a counter to record the event. This circuit is usually connected to a scaler, which is a device that counts and records the pulses it receives.

The scaler used by AEAT was a Harwell Instruments 6000 Laboratory Series, 6255 scaler-timer [65], fitted with Halogen Quenched B12M Geiger Mueller tube from Centronic Nuclear Products [66]. These instruments are quite accurate but the limitation of the sample size and portability do not make them suitable for routine monitoring of large variable size waste items. For this purpose more portable ratemeters connected to NE Technology Ltd. Beta Gamma Probe type BP3 were used. The BP3 probe used in these trials was connected to a ratemeter with an EHT voltage of 300 V to 600 V with an input triggering sensitivity of less than 7.5 V. It can be used to measure beta-gamma radiation

with energies down to ~0.5 MeV [67]. While the ratemeters are devices with electronic arrangements for averaging the count rate over a short period of time (e.g. 5 seconds) and its output is immediate, it is a less accurate statement of count rate. Nevertheless it is possible to calibrate this portable probe/meter combination against known standards, and in particular against samples radioactive contamination that are a representative fingerprint of the contamination found in the cave waste from the WAHF [68, 69]. By taking account of the instrument efficiencies it is possible to correlate radiation levels in terms of dose rate (mSv hr^{-1} or μSv hr^{-1}), counts per second (or minute) and Bq cm^{-2}, generated from different instruments. To this effect the AEAT Health Physics Radiological Services Section at Windscale provide a surface contamination 'ready reckoner' as presented in Figure 2.5a.

As discussed earlier some radiation quickly attenuates in air alone, for example alpha radiation will only travel a short distance in air. Some beta radiation can be shielded by a thin film of aluminium foil, but at certain foil thicknesses and beta particle energies secondary X-ray radiation can be exhibited, known as *bremsstrahlung,* or braking radiation. The beta particles collide with the metal and stop suddenly emitting X-rays, which escape through the remaining thickness of the foil. This is why it is better to use thicker shielding, of even lower molecular weight. The absorption of gamma radiation by air is negligible and its intensity diminishes inversely with the square of the distance from the radiation source. This can be represented as follows:

$$D_1 \times X^2_1 = D_2 \times X^2_2 \qquad \text{.....(2.5.5)}$$

Where X_1 is the distance at dose rate D_1, and X_2 is the distance at dose rate D_2. This is applicable to the beta-gamma radiation found at the WAHF. Clearly the use of shielding can be used to attenuate radiation for the protection of operators, but no such protection can be afforded to the Sponge-jet medium once it captures radioactive contamination when cleaning nuclear waste. The polyurethane medium might be expected to behave in a similar manner to the human body. The level of absorption of radiation will vary depending on the type of radiation and the intensity. The linear energy transfer of charged particles such as alpha particles will be relatively high, while for beta (electron) particles and gamma radiation it will be lower. Nevertheless the higher the radiation levels the higher the damage inflicted through energy transfer that will cause damage at the molecular level. These effects will need to be taken into account in processing polyurethane and whether there are any deleterious consequences for short-term processing and long-term storage and disposal.

FIGURE 2.5a. SURFACE CONTAMINATION READY RECKONER (Counts Per Second (cps) to Bq/cm^2)

	Alpha Contamination (Bq/cm^2)				Beta-Gamma Contamination (Bq/cm^2)						
	Detector Probe Type										
CPS	DP2	DP3	DP6	AP3	BP3	BP4/BP	BP6	DP2	DP3	DP6	1667
1	0.2	0.1	0.05	0.08	0.6	0.4	0.2	0.1	0.1	0.06	0.08
2	0.4	0.2	0.11	0.16	1.6	0.8	0.4	0.2	0.2	0.11	0.16
3	0.6	0.3	0.16	0.24	2.4	1.2	0.6	0.3	0.3	0.16	0.24
4	0.8	0.4	0.21	0.32	3.2	1.6	0.8	0.5	0.4	0.21	0.32
5	1	0.5	0.27	0.4	4	2	1	0.6	0.5	0.27	0.4
6	1.2	0.6	0.32	0.48	4.8	2.4	1.2	0.7	0.6	0.32	0.43
7	1.4	0.7	0.37	0.56	5.6	2.8	1.4	0.8	0.7	0.37	0.56
8	1.6	0.8	0.43	0.64	6.4	3.2	1.6	0.9	0.8	0.43	0.64
9	1.8	0.9	0.48	0.72	7.2	3.6	1.8	1	0.9	0.48	0.72
10	2	1	0.53	0.8	8	4	2	1.1	1	0.53	0.8
15	3	1.5	0.80	1.2	12	6	3	1.7	1.5	0.80	1.2
20	4	2	1.07	1.6	16	8	4	2.3	2	1.07	1.6
25	5	2.5	1.33	2	20	10	5	2.9	2.5	1.33	2
30	6	3	1.60	2.4	24	12	6	3.4	3	1.60	2.4
35	7	3.5	1.87	2.8	28	14	7	4	3.5	1.87	2.8
40	8	4	2.13	3.2	32	16	8	4.6	4	2.13	3.2
45	9	4.5	2.40	3.6	36	18	9	5.1	4.5	2.40	3.6
50	10	5	2.67	4	40	20	10	5.7	5	2.87	4
55	11	5.5	2.93	4.4	44	22	11	6.3	5.5	2.93	4.4
60	12	6	3.20	4.8	48	24	12	6.9	6	3.20	4.8
65	13	6.5	3.47	5.2	52	26	13	7.4	6.5	3.47	5.2
70	14	7	3.73	5.6	56	28	14	8	7	3.73	5.6
75	15	7.5	4.0	6	60	30	15	8.6	7.5	4	6
80	16	8	4.3	6.4	64	32	16	9.1	8	4.3	6.4
85	17	8.5	4.5	6.8	68	34	17	9.7	8.5	4.5	6.8
90	18	9	4.8	7.2	72	36	18	10.3	9	4.8	7.2
95	19	9.5	5.1	7.6	76	38	19	10.9	9.5	5.1	7.6
100	20	10	5.3	8	80	40	20	11.4	10	5.3	8
120	24	12	6.4	9.6	96	48	24	13.7	12	6.4	9.6
140	28	14	7.5	11.2	112	56	28	16	14	7.5	11.2
160	32	16	8.5	12.8	128	64	32	18.3	16	8.5	12.8
180	36	18	9.6	14.4	144	72	36	20.6	18	9.6	14.4
200	40	20	10.7	16	160	80	40	22.9	20	10.7	16
250	50	25	13.3	20	200	100	50	28.6	25	13.3	20
300	60	30	16.0	24	240	120	60	34.3	30	16.0	24
350	70	35	18.7	28	280	140	70	40	35	18.7	28
400	80	40	21.3	32	320	160	80	45.7	40	21.3	32
450	90	45	24.0	36	360	180	90	51.4	45	24	36
500	100	50	26.7	40	400	200	100	57.1	50	26.7	40
600	120	60	32.0	48	480	240	120	68.6	60	32	48
700	140	70	37.3	56	560	280	140	80	70	37.3	56
800	160	80	42.7	64	640	320	160	91.4	80	42.7	64
900	180	90	48.0	72	720	360	180	102.9	90	48	72
1000	200	100	53.3	80	800	400	200	114.3	100	53.3	80
1500	300	150	80.0	120	1200	600	300	171.4	150	80	120
2000	400	200	106.7	160	1600	800	400	228.6	200	106.7	160
2500	500	250	133.3	200	2000	1000	500	285.7	250	133.3	200
3000	600	300	160.0	240	2400	1200	600	342.9	300	160	240
3500	700	350	186.7	280	2800	1400	700	400	350	186.7	280
4000	800	400	213.3	320	3200	1600	800	457.1	400	213.3	320
4500	900	450	240.0	360	3600	1800	900	514.3	450	240	360
5000	1000	500	266.7	400	4000	2000	1000	571.4	500	266.7	400

Materials and waste must remain in controlled areas

Materials and waste may remain in controlled areas

Materials and waste may be allowed into Non-controlled areas

2.6 NUCLEAR WASTE AND DISPOSAL ROUTES

Generally nuclear waste has levels of radioactivity that places it into one of several categories: High Level Waste (HLW), Intermediate Level Waste (ILW), Low Level Waste (LLW), and non-nuclear Very Low Level Waste (VLLW), or clean non-active waste. Generally HLW, ILW and LLW are generated from nuclear site operations. In addition to this there are categories of exempt waste; where very specific types and forms of waste comply with the conditions of an exemption order, it may be possible to dispose of it in a manner similar to clean non-nuclear waste e.g. controlled burial at landfill sites. These wastes usually possess radioactivity levels at the bottom or below the LLW category. These exemptions are usually quite specific and apply prescriptive conditions to particular types of waste e.g. Prepared Uranium and Thorium Compounds, and the Phosphatic Substances Exemption Orders [70, 71]. The Substances Of Low Activity Exemption Order [72] provides for free release of general solid wastes if it can be demonstrated unequivocally that the waste is below 0.4 Bq g^{-1} for solid radioactive wastes. Generally nuclear waste will need to be clearly below the limits of activity for each category, otherwise where there is any doubt it may have to be categorised in the higher level. For nuclear waste to be categorised as clean the radioactivity levels must be shown to be so low that it is not radioactive waste as defined under the RSA93 [40]. In this category the waste materials could if practicable be recycled, but solid waste would again need to be below 0.37 Bq g^{-1}, unless it can be claimed that only specific radionuclides are present such as uranium (excluding daughter products) where the de-minimus level is set at 11.1 Bq g^{-1} [40]. It is unlikely that wastes generated by the WAHF or sent to these facilities from elsewhere in the nuclear industry will be able to claim these specific exemptions. Therefore the target for this work will be the 0.37 Bq g^{-1} limit, and a

complimentary surface concentration of 4 Bq cm^{-2}. This is conservative since most waste materials will possess surface areas of 1 cm, with at least 1 g of material attached.

There is no specific HLW generated at the WAHF. HLW is usually a by-product of fuel reprocessing (e.g. containing high concentrations of long-lived fission products that are highly radioactive and heat generating) which is carried out by BNFL. It is the processing of this fuel through the WAHF that gives rise to contaminants that create ILW. These contaminants arise from reactor fuel material that is the subject of various examinations and experiments within the facilities. This fuel could be intact, dismantled or cut up, where the cladding containment is lost. The post experimental fuel form dictates the nature of its disposal to BNFL for reprocessing and recycling. Fuel is transferred through a number of plant items/areas before it is reprocessed such as posting ports, flasks, and storage ponds, where the spread of contamination must be controlled and minimised. Intact fuel assemblies can usually be despatched directly to BNFL in line with their standard process route from the reactor stations. Dismantled intact fuel pins or rods are sent to BNFL packed into slotted containers. This permits pond-water access to the container during storage and reflects the fact that the intact fuel cladding prevents direct access to the fuel. Fuel with damaged cladding on the other hand, must be packed efficiently into containers that must be sealed by welding. This prevents or minimises the potential egress of contaminants during transport to, and during pond storage [73] and therefore the generation of secondary wastes. At the WAHF the equivalent secondary waste arising are the materials, tools and equipment used to carry out the experiments within the caves which get contaminated and generally become ILW, and currently there are few options beyond volume reduction (concentration) of waste material.

ILW from the WAHF operations consists of material arising from the in-cave active operations that has become so contaminated that it has radiation levels above 7.5 mSv hr^{-1} $\beta\gamma$, and activity levels greater than 12 GBq te^{-1} $\beta\gamma$ [74]. At levels below this the waste could be considered to be LLW. The high fissile material content of contamination at the WAHF invokes another control of 10 g ^{235}U and total Pu per package. This is a precautionary limitation to provide additional assurance against any situation where criticality might be approached during any subsequent storage/disposal arrangement. This tends to be the upper limiting factor for ILW disposal to the BNFL interim waste store. This is operationally controlled by direct radiation monitoring of packages prior to consignment, based on standardised 'fingerprints' taken from the cave system [68, 69]. The majority of this waste takes one of two forms: either hard metallic materials such as redundant storage containers, test rigs, tools and other equipment, or soft materials such as tissues, mop heads and various polymeric items. Material that has spent any time in the cave system could not be considered as LLW without considerable decontamination which at present is not economic or justifiable on radiation dose uptake grounds. This material is therefore collected for remote in-cave volume reduction and efficient packing prior to despatch to the BNFL interim ILW store (MBGWS) within shielded flasks. Packing densities obtained for hard wastes are often little more than 30 % at best, even after compaction (if possible). Soft wastes can sometimes achieve a 60-70 % packing density, but this is after some considerable preparation of the waste to get it into a compactable position and the addition of specialised cans for compaction which in themselves add to the waste volume.

LLW is usually generated as waste materials from low active operations outside the cave system, such as low level cleaning operations on floors, clothing, tenting etc. Any

material that is above the LLW limits should be redirected as ILW. There are limits on radiation (7.5 mSv hr^{-1} $\beta\gamma$) and on activity per unit mass (12 GBq $te^{-1}\beta\gamma$) for LLW. Some high volume and high-mass materials are clearly LLW, such as redundant crane gantry and other structural steelwork. With other waste materials it may not be so clear cut whether they are above or below the limits, due to concealed surfaces/self shielding uncertainties about mass etc.. Nevertheless the monitoring assessment, and packaging of such waste must be sufficiently robust as to demonstrate that wastes are not disposed through an inappropriate route, and ensure that higher category waste is not effectively diluted within radiation and specific isotope package limits for disposal via a lower level waste route. The level at which waste can be released for non-active disposal is 0.37 MBq te^{-1}, and 3.7 Bq cm^{-2}(or 0.4 MBq te^{-1} if the SOLA EO is used) [40, 72]. In order to verify that material is clean below these demanding limits there must be unimpeded access for radiological monitoring. Painted or corroded materials cannot be monitored to this level since there is the possibility that radioactive contamination is entrained in and shielded by these surface layers. The cost of removing these layers is considered uneconomic using the technologies previously available, even though the dose penalty may be very small. This waste is usually packed into ISO freights in accordance with BNFL authorisation and acceptance criteria [74, 75] for despatch to the Drigg LLW disposal facility. The ISO freights are then filled with grout to immobilise contamination and minimise voidage. The ISO freights are then loaded to the Drigg disposal facilities (concrete lined trenches) where they are grouted in-situ. Alternatively large solid items such as flasks can go to directly to Drigg for in-situ grouting subject to the acceptance criteria.

All other waste, if demonstrated to be radiologically clean, can be technically disposed of or recycled at minimal cost through non-nuclear routes, although obtaining acceptance for this disposal is not so easy in practice. Many non-nuclear industries are understandably reluctant to take materials from the nuclear industry for recycling (e.g. the steel industry) due to the perceptions of their customers and the effect it will have on their business. Nevertheless there are opportunities that may develop for such materials to be recycled back into the nuclear industry, rather than any public domain. The difference in cost between this and the various nuclear waste categories are very large. LLW can cost up to £5 k m^{-3}, while ILW disposal costs can be in excess of £0.5 M m^{-3}, and could rise to more than £1 M m^{-3} depending on when a final disposal route becomes available. These factors provide compelling reasons why waste generators within the nuclear industry should minimise their ILW and LLW volumes as much as possible, and serve to promote the decontamination of waste as a key aspect of waste materials management in the nuclear industry. With the introduction of the new Nuclear Decommissioning Agency (NDA) where a key driver is 'value for money' this approach will be given very close scrutiny to ensure every 'tax payers' pound is well spent. The Sponge-jet process could provide an environmentally acceptable economic means of achieving this within the WAHF.

2.7 OBJECTIVES OF RESEARCH

The ultimate goal of this work is to develop an integrated process for reducing hard 'metallic' and soft 'polymeric' active waste volumes at the WAHF. As a limited part of this objective the work aims to develop a sound knowledge base in proving a viable decontamination and PU volume reduction technique. In order to realise this objective the following requirements will be met;

1. A definition of PU material behaviour involved in decontamination and volume reduction.

2. An evaluation of process performance, through inactive and active trials.

3. An evaluation of the data gained, to assess the potential economics of individual parts and the process overall.

This work may raise further questions as to the final process design, where secondary waste characterisation and long term PU storage stability issues need to be addressed. This will be the subject of further studies, as discussed in chapter 5 and the concluding remarks. Nevertheless the research programme described in the following chapters will aim to justify pursuing this work to produce a complete process solution for the minimisation of 'hard' metallic, and 'soft' polymeric LLW and ILW.

2.8 SUMMARY

This background chapter has demonstrated the novel or even unique nature of the work to be described in subsequent chapters. A background has been provided on the unique facilities within which any new waste management system would be deployed. A review of current legislation, government policy and the regulatory framework used to enforce that policy has been presented. A description of the processes and materials that will be involved in this work has outlined that the Sponge-jet surface treatment process will be evaluated to assess whether it can be adapted for use as a decontamination tool within an integrated waste management system. This involves the processing and interaction of polyurethane foam and film with radioactively contaminated metallic waste. A key

material is the contamination material itself and its transfer response to interaction with the polyurethane materials during Sponge-jet decontamination and subsequently volume reduction. Some background has also been presented to put the radiation and contamination found in radioactive waste at the WAHF, along with the waste disposal routes to which these materials are currently directed into context. This is in order to appreciate how any new waste processing system may redistribute waste volume and type throughout the waste category hierarchy.

CHAPTER 3 EXPERIMENTAL DETAILS

3.0 INTRODUCTION

The work required to evaluate whether the sponge blasting technology could be applied to nuclear waste decontamination within the B13 Active Handling Facility at Windscale will require several experimental approaches, all of which, if successful need to be brought together to provide an integrated total solution for managing solid metallic and polymeric wastes contaminated radioactively.

Firstly, the blast process needed to be evaluated in its own right (inactively – without radioactive materials) to determine and/or confirm its operating characteristics. Secondly, an experimental strategy would be required to develop experimental apparatus and systems in order to evaluate the process on radioactively contaminated materials. The latter would need to be staged so that the research could support safety management approvals for more highly active work, so initially a low level waste experiment was designed with a view to more highly contaminated waste cleaning experiments being performed later.

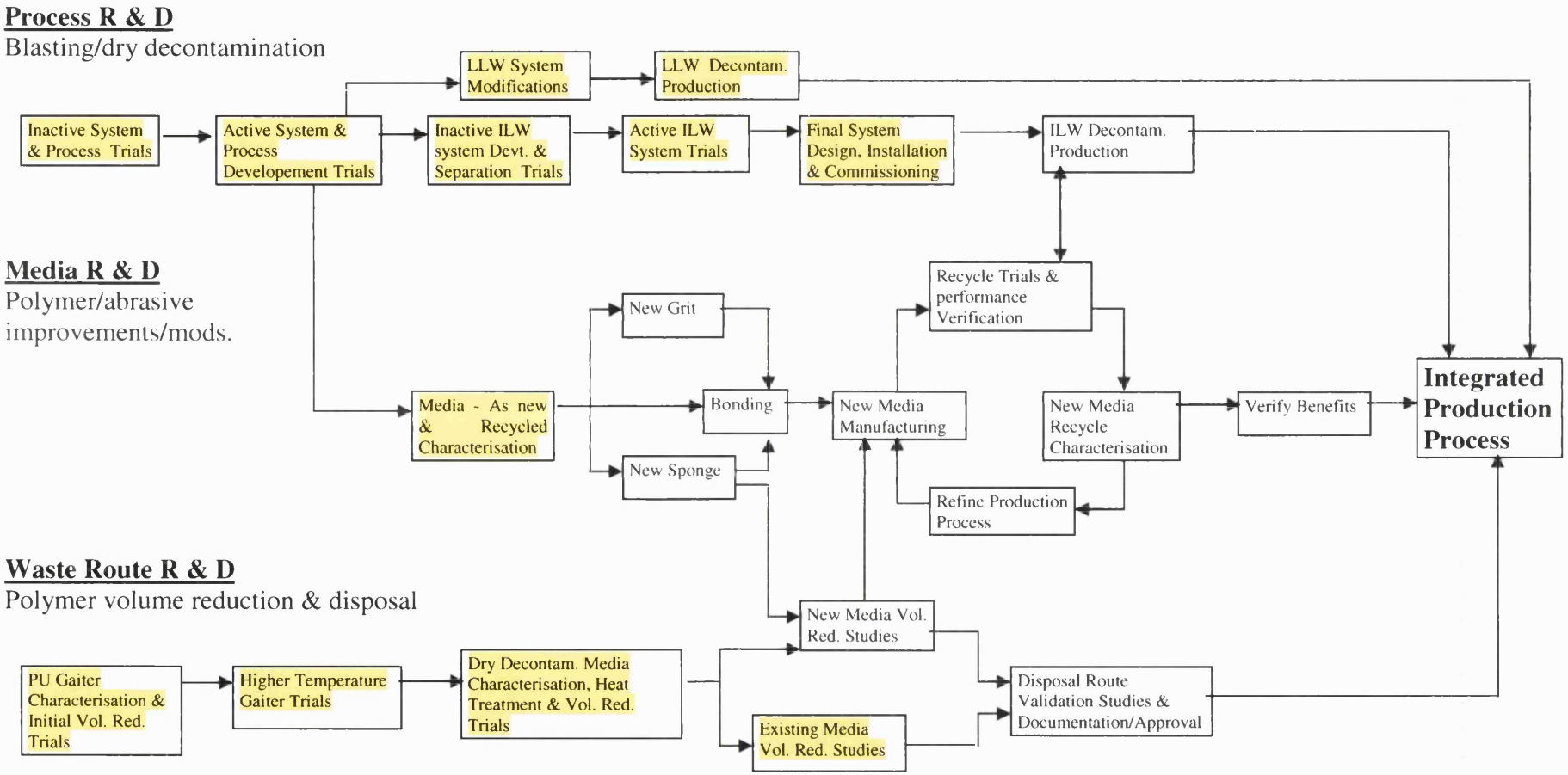
Running in parallel with these blasting experiments a number of studies have been required to demonstrate that the polyurethane foam particle medium could be managed effectively within the B13 Facilities. This includes demonstrating that it can be packaged in a manner suitable for LLW or ILW disposal. This area of study has been extended to the processing of other polyurethane materials generated within the B13 cave system, such that they might be disposed through the same route. This work is also needed to

provide a basis on which long-term safety within an interim storage facility and subsequent final disposal repository for post closure conditions could be evaluated.

Another area of study, and potentially very important, is the development of a 'nuclear specific' cleaning medium. The media that has already been developed for different non-nuclear uses, and it was recognised at an early stage that there might be possible avenues of improvement that could be made to a medium to enhance its performance for radioactive waste decontamination. This area of study would necessarily lag behind the other areas of study, but the physical assessment of used medium has been included to identify any life limiting parameters. These should feed directly in to any media research and development that may ensue from this work and follow later.

Figure 3.0a shows a flow diagram representing the original project plan for this work through to an ultimate solution should all stages prove successful. It has only been possible to take this work so far down the planned route to completion and the broad areas covered are highlighted in yellow. The design and conduct of the experiments described in this section have been aimed at evaluating a number of process parameters and characteristics and will be discussed at each stage of the work. Table 3.0a summarises these factors and the stage at which they have been examined. Due to regulatory and financial constraints it was not always possible to conduct all experiments to a level that would permit study in to every characteristic or parameter of the process. For example, radiation dose uptake to workers in the nuclear industry must be minimised to levels that are as low as reasonably practicable (- the ALARP principle covered under the ionising radiation regulations, IRR 99 [62]). Where possible comment and a rationale

FIGURE 3.0a: OUTLINE PLAN FOR THE RESEARCH PROJECT INTO WASTE DECONTAMINATION AND VOLUME REDUCTION AT B13



(Areas of the project plan covered in this thesis are highlighted in yellow)

TABLE 3.0a: AREAS OF STUDY AND RELEVANT CHARACTERISTICS, PARAMETERS AND RELATIONSHIPS

Study Area	Characteristics	Parameters/Relationships	Source
Initial Trials (inactive)	Blast System	Operating Pressures - Supply - Vessel - Nozzle	Supplier – O & M manuals(76)
		Flow Rates - air (m^3) - speed ($m.s^{-1}$)	Supplier – O & M manuals(76)
		Deployment - blast coverage - stand off - feed - cutting rate - material type removal	Experimental
		Material/Medium - consumption - Recycle	Supplier/Experimental
		Blast pressure/consumption(&+recycle)	Experimental
		Blast pressure/coverage(for stand off)	Experimental
		Blast pressure/coverage(for feed rates)	Experimental
		Stand off/cutting rate	Experimental
		Material type/cutting rate	Experimental
	Media	Material type (polymer, abrasive)	Supplier – Material data sheets(56, 57)
		Density	Supplier – Material data sheets(56, 57)
		Particle size & weight(overall, abrasive, & recycled)	Supplier/experimental
		Chemical make-up	Supplier/Experimental
		Particle structure(as new & used)	Experimental
		Particle structure/Recycles	Experimental
		Abrasive/Non-abrasive	Experimental
		Impact mode	Experimental
		Material removal mode	Experimental
		Containment mechanisms	Experimental
		Heat treatment characteristics	Experimental
	Operation	Medium vol.: Area cleaned	Experimental
		Decontamination rates/factors	Experimental
		Radiation effects	Experimental
		Airborne contaminants	Experimental
		System Contamination Transfer	Experimental
		Waste activity	Experimental

will be made as to the likely effect or outcome on those relevant areas of the process should studies be less than complete.

3.1 INITIAL TRIALS

3.1.1 Equipment Description

Blasting Trials

The equipment and materials required for undertaking the initial inactive decontamination trials are listed in Table 3.1a. This work was necessary to establish or confirm some of the basic parameters of the Sponge-jet decontamination process, and its applicability for further radioactive studies.

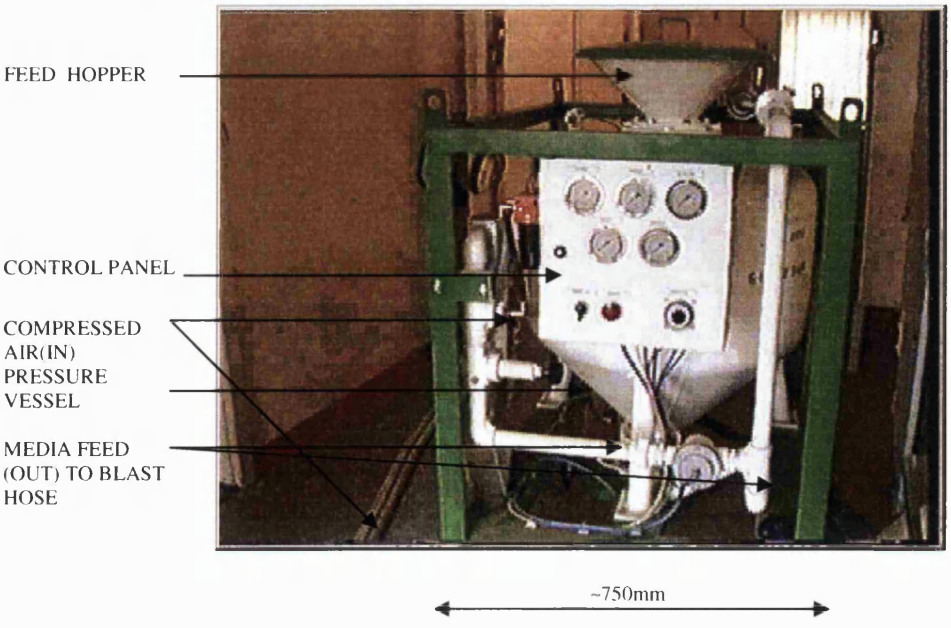
TABLE 3.1a: DETAILS OF EQUIPMENT AND MATERIALS USED IN THE INITIAL INACTIVE BLASTING TRIALS

Equipment / Materials	Description
Spongejet Blasting System	240 Litre Feed Unit
Compressor	After cooled capable of delivering $6m^3$ of oil-free air at 0.7 MPa
Media Grading System	Pneumatic drive vibration on inclined two stage wire mesh bed
Blasting Booth	Wooden base tray with raised back face to incorporate waste clamping system. Frame attached to hang plastic containment
Silver sponge medium	Polyurethane foam particles containing abrasive aluminium oxide grit (bulk density ~535 $Kg.m^{-3}$)
Green sponge medium	Polyurethane foam particles only
Waste Simulations	Three 600 mm square plates of mild steel(43A), stainless steel (304) and aluminium (L54) (each nominally 6mm thick)
Personal Protective Equipment (PPE)	Integral dust mask and visor, gloves, ear defenders, overalls and protective apron
Collection and Sampling Equipment	Dust pan and brush, collection bags, sample containers

The Sponge-jet blasting system consists of a simple pressure vessel, with a hopper and valve charging arrangement at the top, and a blast stream feeding arrangement at the bottom, a control system and support motors (air) to drive vibration and feed mechanisms. Figures 3.1a and 3.1b describe the overall arrangement, which is mobile, in that wheels are fitted to the frame and lifting yokes permit hoisting by crane. Figure 3.1c [76] shows in section the charging arrangement at the top of the vessel, which includes a pop-up valve

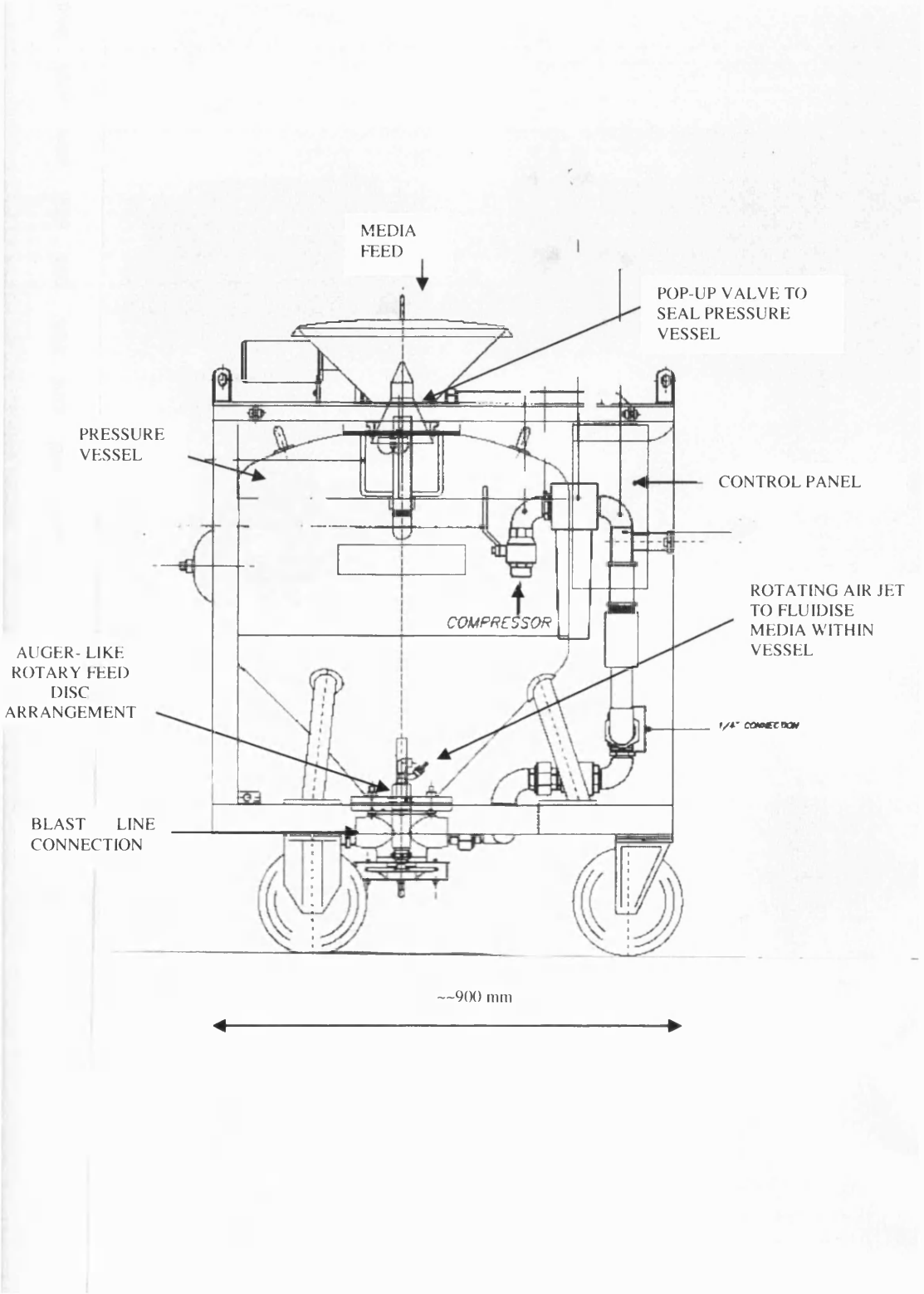
[76] that seals the vessel when running. When the system is not running this valve drops enabling the vessel to be recharged. The vessel can contain just less than one quarter of a metre cubed of medium. Figure 3.1d shows the lower vessel arrangement [76] where media from within the vessel is managed into the main blast stream. This mechanism is mounted on a flange at the base of the vessel and is driven by an air motor through chain and sprockets. Since media will not simply feed by gravity from the vessel it is fluidised by an air flow up through the impeller shaft that is discharged above the impeller-disc that feeds the media in a controlled manner by deflection vanes into main blast/delivery air stream. The fluidisation of the media effectively prevents "bridging or clogging" and ensures a uniform flow of media, and hence discharge from the blast nozzle. This is complemented by a system that imparts vibration to the vessel. The faster the air motor operates, the more media that is delivered. During operation approximately 30 % of the compressor supply is diverted to operate these systems, and at maximum blast pressure through to the 9 mm diameter nozzle is ~0.48 to 0.49 MPa delivering ~4.1 to 4.2 m^3 of air at prevailing ambient atmospheric conditions.

FIGURE 3.1a: THE SPONGE-JET BLASTING SYSTEM



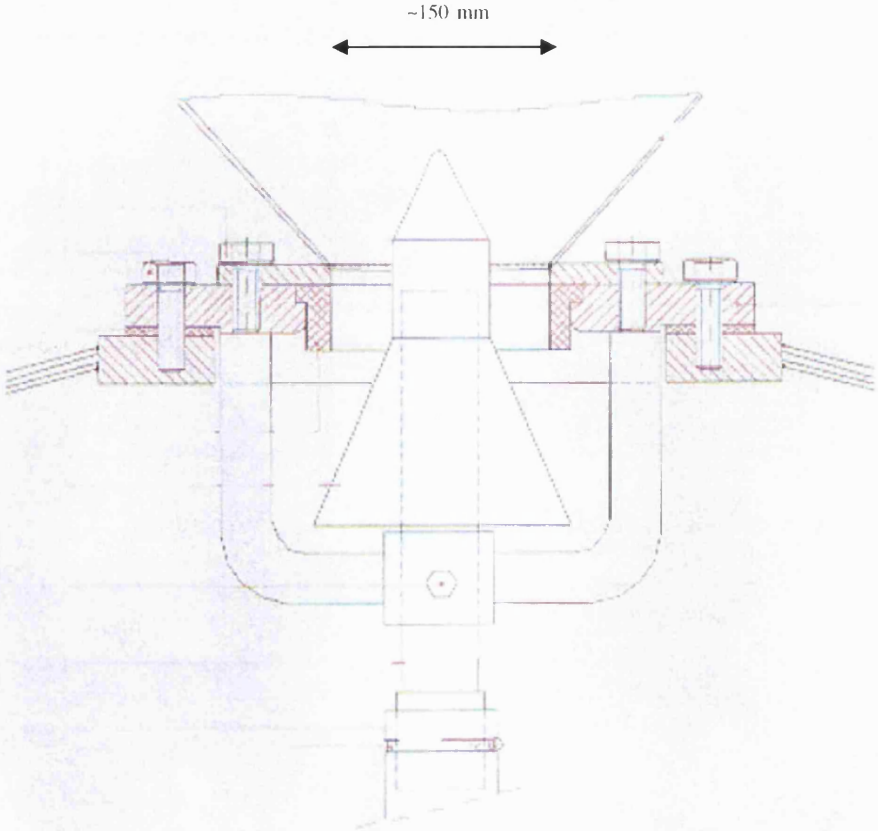
Front view of the blast system with the control panel in front of the pressure vessel

FIGURE 3.1b: THE SPONGE-JET BLASTING SYSTEM



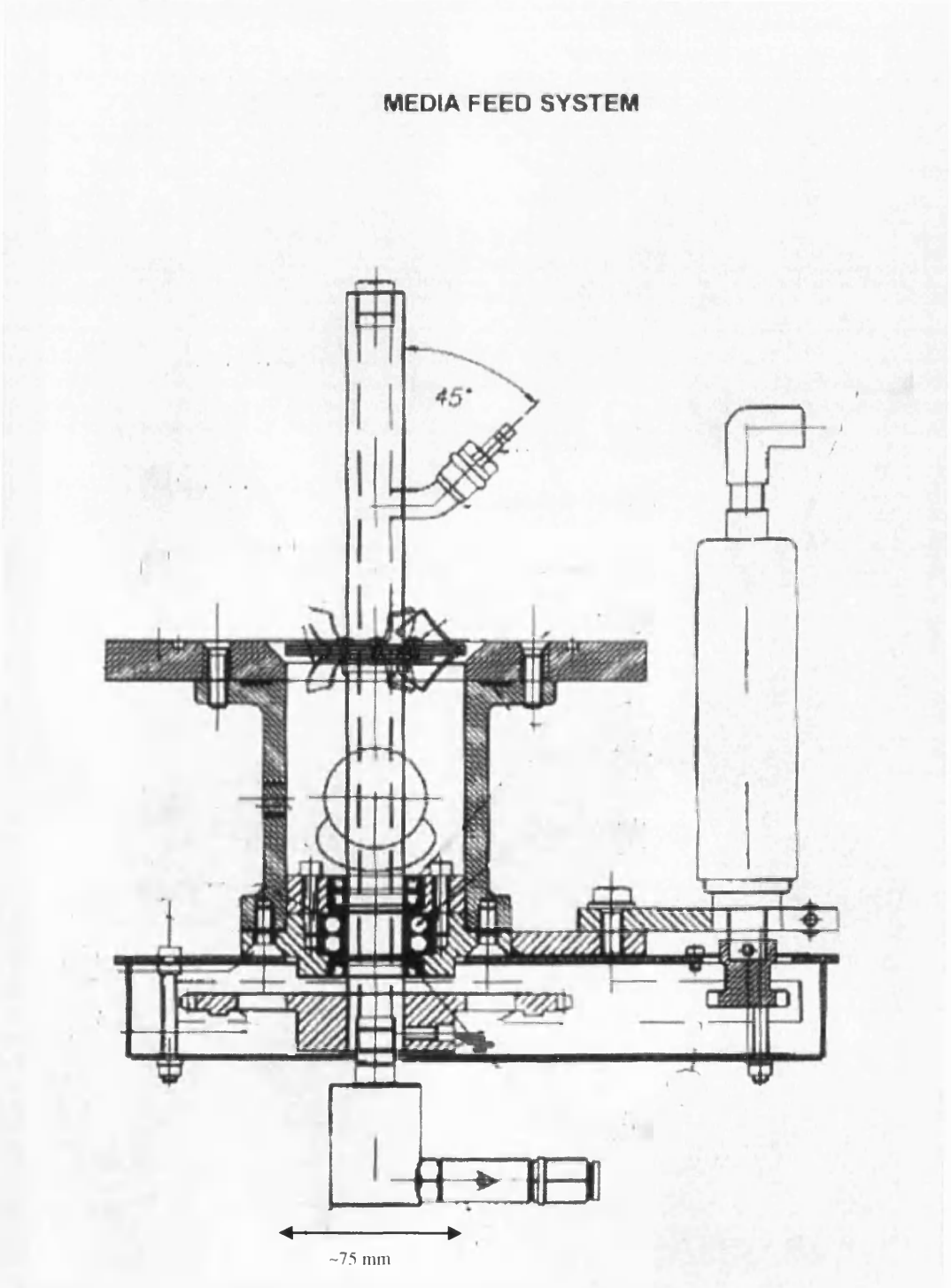
Side view of the blast system in section within its support frame (~1.6-1.7 m high)

FIGURE 3.1c: VESSEL HOPPER AND POP-UP VALVE



Cross-sectional view of the loading hopper and valve at the top of the pressure vessel: when the vessel is not pressurized to enable loading of media the valve drops, and when the vessel is pressurized ready for blasting the valve 'pops-up' to seal the system.

FIGURE 3.1d: LOWER VESSEL MEDIA FEED ARRANGEMENT



Cross-sectional view of the media feed mechanism at the bottom of the pressure vessel: centred around a hollow spindle rotated by a chain drive from an air motor (right) air is fed into the vessel to keep the media 'fluidised', while a specifically designed feed disc is used to capture media and send it down into the blast hose air stream without blocking.

The Sponge-jet feed unit is completely operated from the control panel (see Figure 3.1a and 3.1e). The system controls and provides gauge indication for main line pressure, blast air pressure, media flow pressure, flow pressure, and blast pressure. Furthermore there are on/off remote switch, red emergency stop, and media flow control regulators. There is a main line isolator and moisture separator and lubricator.

Since the sponge media can be recycled it is collected after each blasting session for reuse. Unfortunately there is a finite life for the media in that it begins to break up and can only be recycled so many times depending on the media type, blasting pressures and cleaning process being undertaken. The supplier recommends grading the recycled media to remove the fine material that is created during this break up process, to maintain effective cleaning during each recycle session. The grader described in Figure 3.1f, where an inclined mesh bed consisting of two sieves, is sized to separate out fine materials from the larger reusable media. The upper sieve has a mesh of 2 (aperture size of 10 mm), and the lower bed has a 16 mesh size (aperture size of 1 mm) [6]. Used media from between blast sessions is fed on to the top end of the upper sieve via a hopper, while the mesh bed is vibrated using a rotary belt system driven by an air motor supplied through the blasting system from the compressor. A dam separates the two sieves to hold up the media for a while to ensure that all fine material escapes, leaving only larger media particles to pass over into, and through, the larger sized sieve for reuse. Bags or boxes are used to collect the fines and reusable media separately.

[6] Private communication in 1998 with Mr A Wilks, Sales Manager, Sponge-jet UK.

FIGURE 3.1e: PNEUMATIC CONTROL SYSTEM (provided courtesy of Sponge-jet UK)

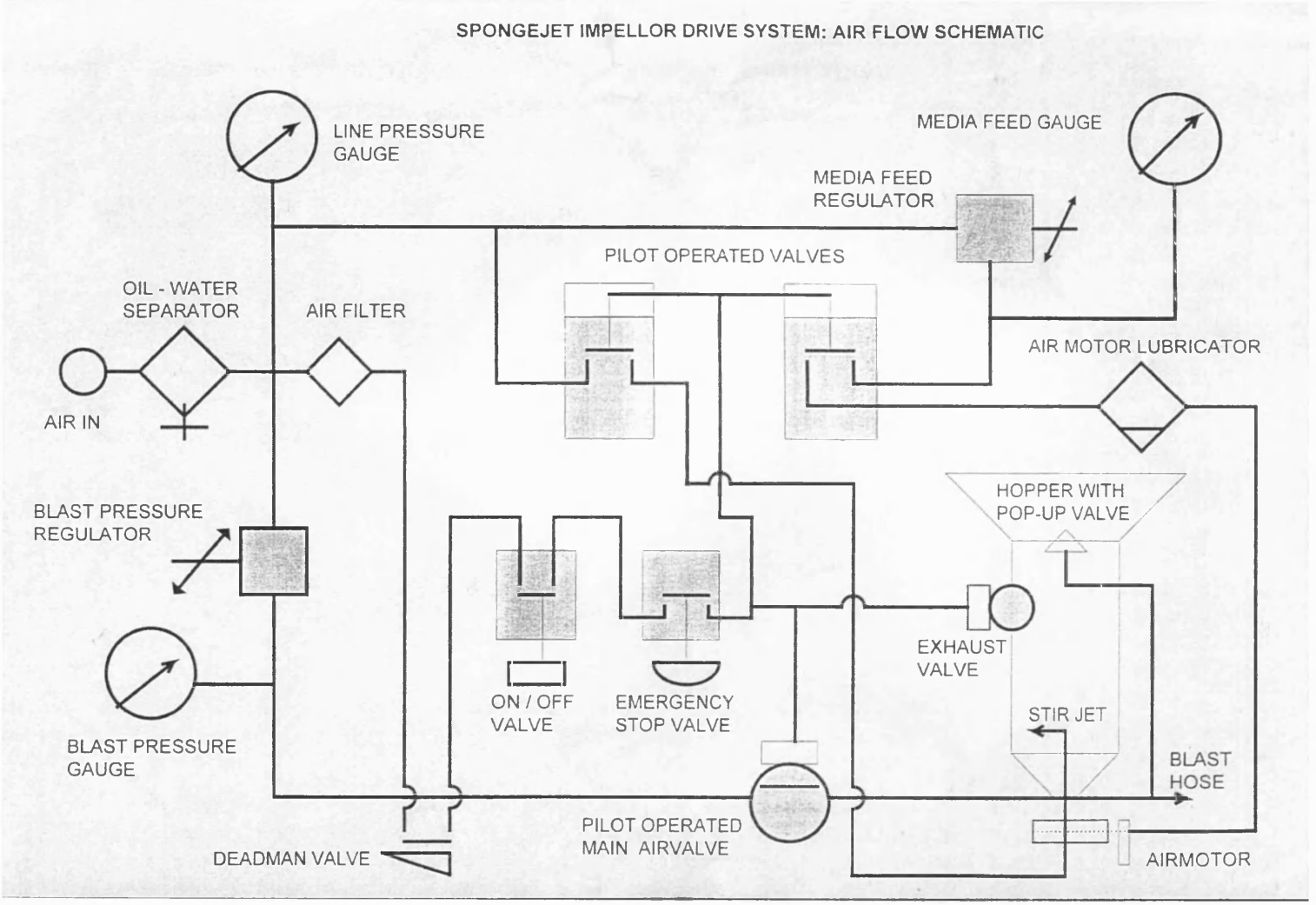
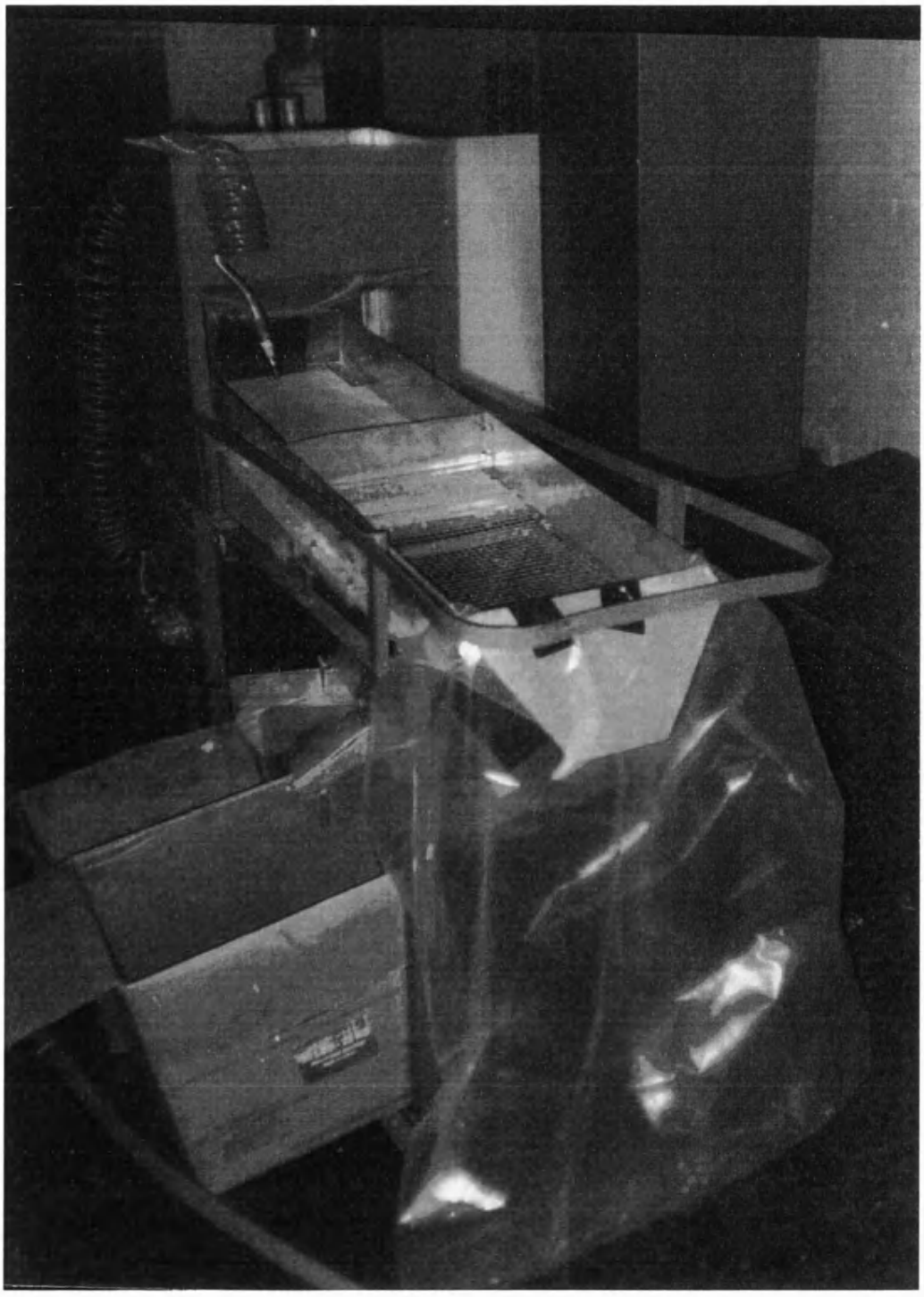


FIGURE 3.1f: MEDIA GRADING SYSTEM



~300 mm

A view of the mechanical sieve system for separating fine waste media from reusable media between passes – this arrangement is not suitable for radioactive work

The blast booth was essentially a wooden tray with sides raised to ~300 mm at the front and sides, and ~600 mm at the rear (to support framework for holding test pieces for blast trials). A metal frame was constructed and attached to the tray in order to hang a tent made from plastic sheeting. This completed a containment system which was sealed with tape preventing media escaping during blast sessions, enabled it to be collected using brush and shovel, and at the same time, allowed access and egress for the operator. This was a simple arrangement that permitted the sponge blasting system to be evaluated in a controlled manner and is presented in Figure 3.1g.

FIGURE 3.1g: SPONGE BLASTING CONTAINMENT SYSTEM FOR INACTIVE TRIALS

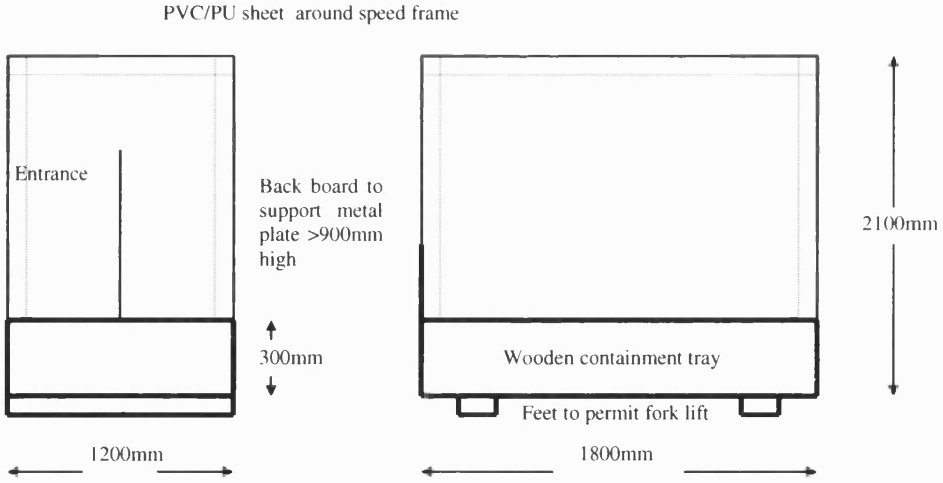


FIGURE 3.1g (Continued)

Containment Tent Entrance

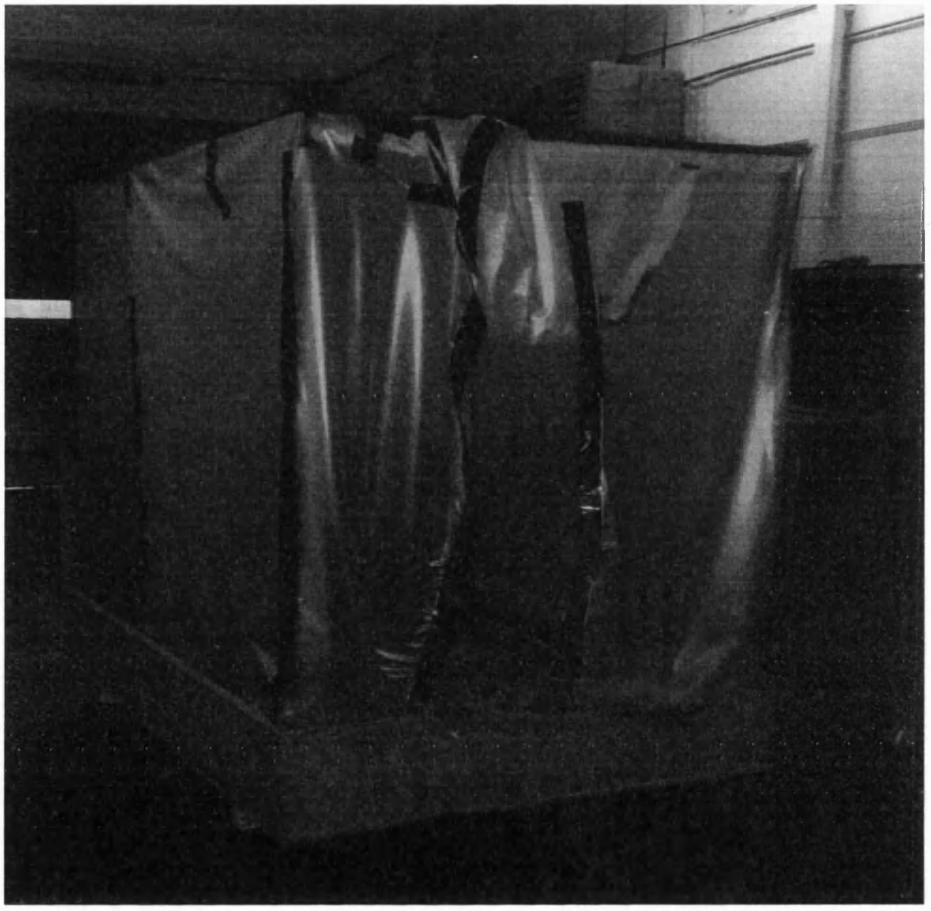
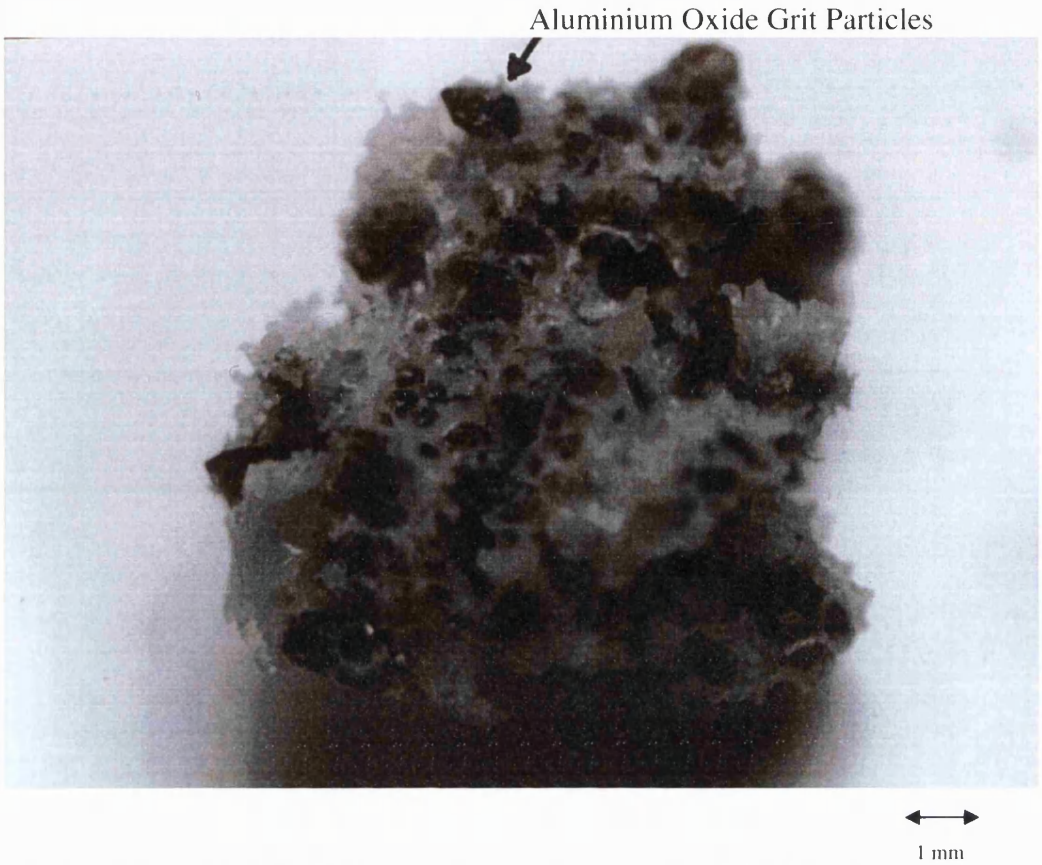


Plate Samples Supported Inside Tent

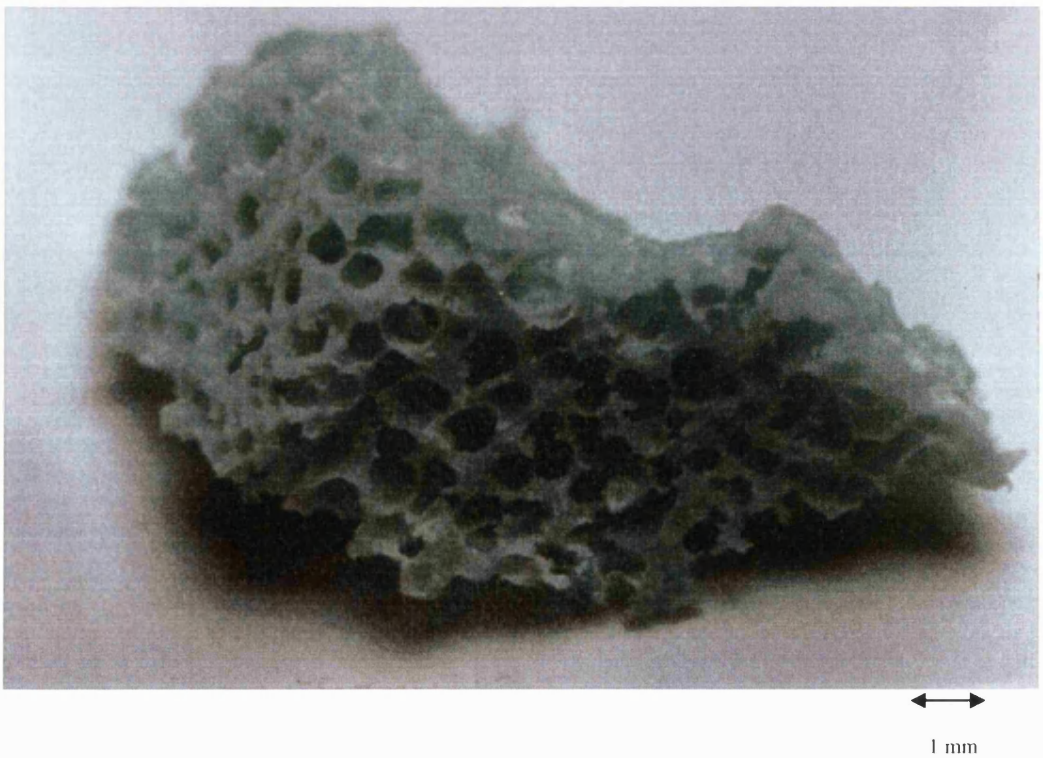
The media selected for these trials was restricted to 'Green' non-abrasive medium and 'Silver' abrasive medium. Even though other media types were available these were the most appropriate for the ultimate objective of radioactive waste cleaning. The Silver medium contains aluminium oxide particles and was one of the most aggressive media available, remaining relatively stable under damp conditions. The alternative Brown medium containing iron oxide particles is prone to corrosion and therefore deterioration in its performance, which may occur following periods of storage before, during or after use. Also since it is waste that is being cleaned there is no benefit in cleaning material lightly if there is a possibility that areas of ground-in contamination may not be removed, so it is advisable to use the most aggressive media available, hence Silver medium. The only exception to this is where tools and equipment have become so contaminated that they can not be refurbished using 'hands-on' methods due to the radiation dose uptake that would be incurred by individuals working on that equipment. While Silver medium would clean such equipment its abrasive effect would actually render it useless. Green medium offers the possibility that tools and equipment could be cleaned to levels of contamination that give rise to much lower radiation, and hence dose uptake to operators repairing them would be reduced. This tooling and equipment is therefore less likely to become waste. Figure 3.1h provides further information on the Silver and Green media and depicts typical as-new particles.

FIGURE 3.1h: SILVER AND GREEN MEDIA PARTICLES

Macroscope view of Silver (abrasive) Medium



Macroscope view of Green (Non-abrasive, no grit particles) Medium

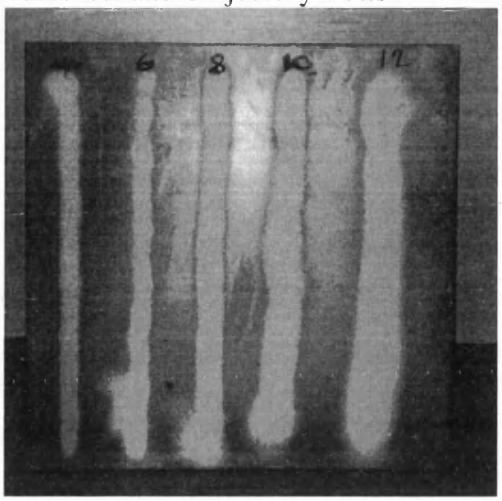


The materials chosen for use in the initial trials included stainless steel (304), mild steel (43A), and aluminium (L54) plate. The material was old stock available in the machine workshop and chosen to represent the range of metallic material to be decontaminated in the WAHF. Each plate was nominally 600 mm by 600 mm by 6 mm thick, and these material types represent over 95% of the metallic waste dealt with in the Windscale Active Handling Facilities. Some 'real-life' tests were done to see the effects of the process e.g. on corroded lifting shackles.

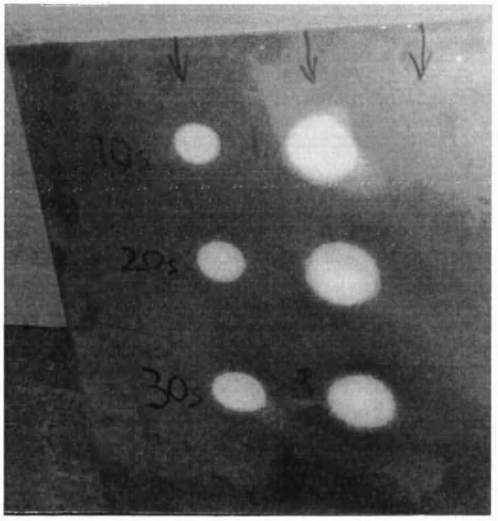
All blasting trials were conducted using appropriate Personal Protective Equipment (PPE), with trials and sampling carried out at each stage in order to conduct studies in to changes in the medium during recycling, its effect on the materials being tested and on bulk performance. Examples of this process are shown in Figure 3.1i, medium was collected in small aluminium screw top tins, and specimens were machined from the plate materials after the trials. Firstly trajectory and stand-off trials were undertaken along each plate, and time trials were undertaken at fixed points and different stand-offs on the reverse side. Since the active trials would be on waste material, trial blast pressures were set to the maximum at ~480-490 kPa (~70 p.s.i). To investigate the cutting effects of the medium on the material surfaces, specimens were trepanned from the blasted areas for further examination.

FIGURE 3.1i: SAMPLING OF TEST MATERIALS DURING INITIAL TRIALS

Stand-off and Trajectory Runs

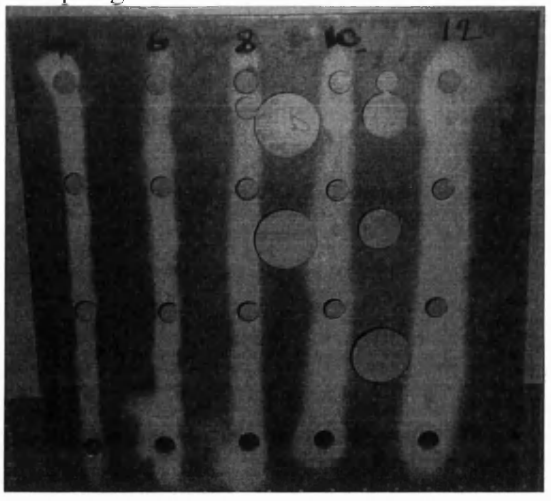


Time Trials



~600 mm

Sampling Points



Polymer Volume Reduction (initial trials)

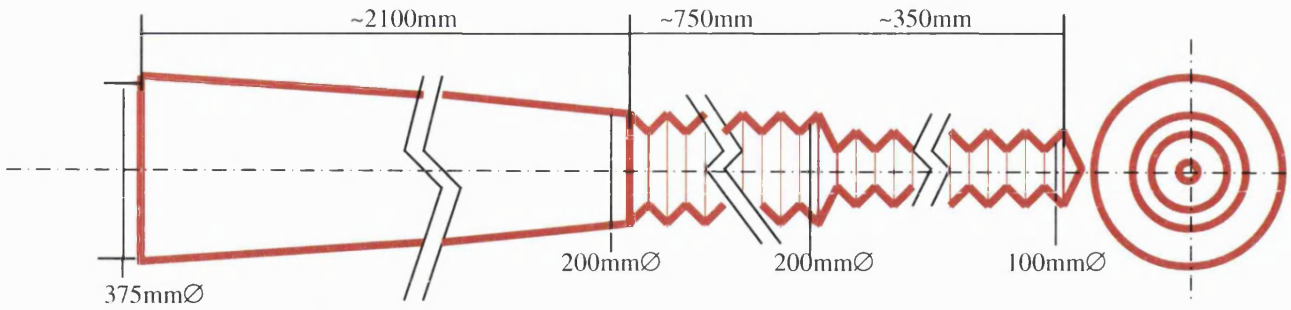
The equipment and materials required for undertaking the initial inactive polymer volume reduction trials are listed in Table 3.1b. This work was necessary to establish or confirm some of the basic materials characteristics and behaviour in a potential heat treatment process, and its applicability for further radioactive studies.

TABLE 3.1b: DETAILS OF EQUIPMENT AND MATERIALS USED IN THE INITIAL INACTIVE POLYURETHANE VOLUME REDUCTION TRIALS

Equipment / Materials	Description
Spongejet Media	Green and Silver types for test samples.
One Unused Old Gaiter	This is a sleeve used to cover Remotely Operable Manipulators at B13 and protect them against contamination. For provision of samples
Radiant Lamp Heating System (inc. control system)	Designed to fit on a disposal container and input heat to the polymer material once placed inside the container.
Disposal Container (modified for trials)	Standard disposal container used at the Windscale Active Handling Facilities.
Thermocouples and temperature measuring system.	Platinum wire t/c's for measuring the container inner temperature during trials
Personal Protective Equipment (PPE)	Integral dust mask and visor, gloves, ear defenders, overalls and protective apron
Collection and Sampling Equipment	Dust pan and brush, collection bags, sample containers

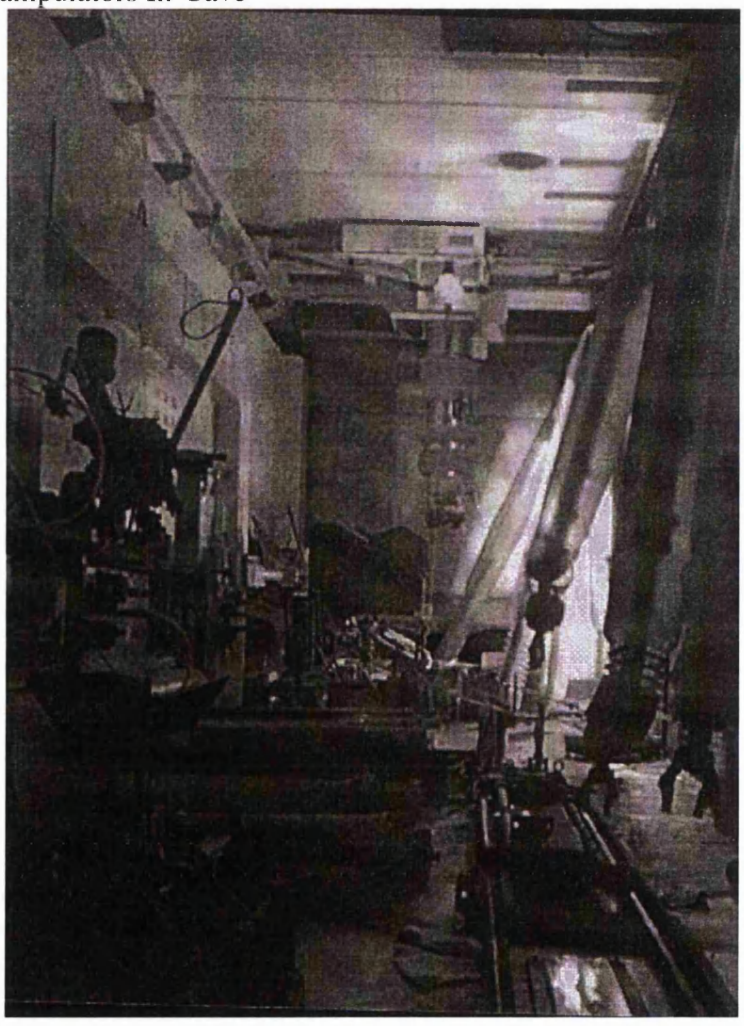
The media samples consisted of unused samples of the types described in Figure 3.1h. Figure 3.1j describes a gaiter and shows the gaiters in use on manipulators being remotely operated in the WAHF caves. An unused example of the type used was made available to the project. The polyurethane material is the same as the material used to make the gaiters currently stored in cave for disposal. Gaiters are now made from PVC, but the stored gaiters represent a backlog of used polyurethane gaiter material that needs to be disposed of in a cost-effective manner.

FIGURE 3.1j: POLYURETHANE GAITER



Gaiter Dimensions

Gaiters On Manipulators In-Cave



The heating system consisted of three Phillips IRZ 1000 W halogen heat lamps, set in a cowling that is designed to fit on top of a standard waste disposal container. The control

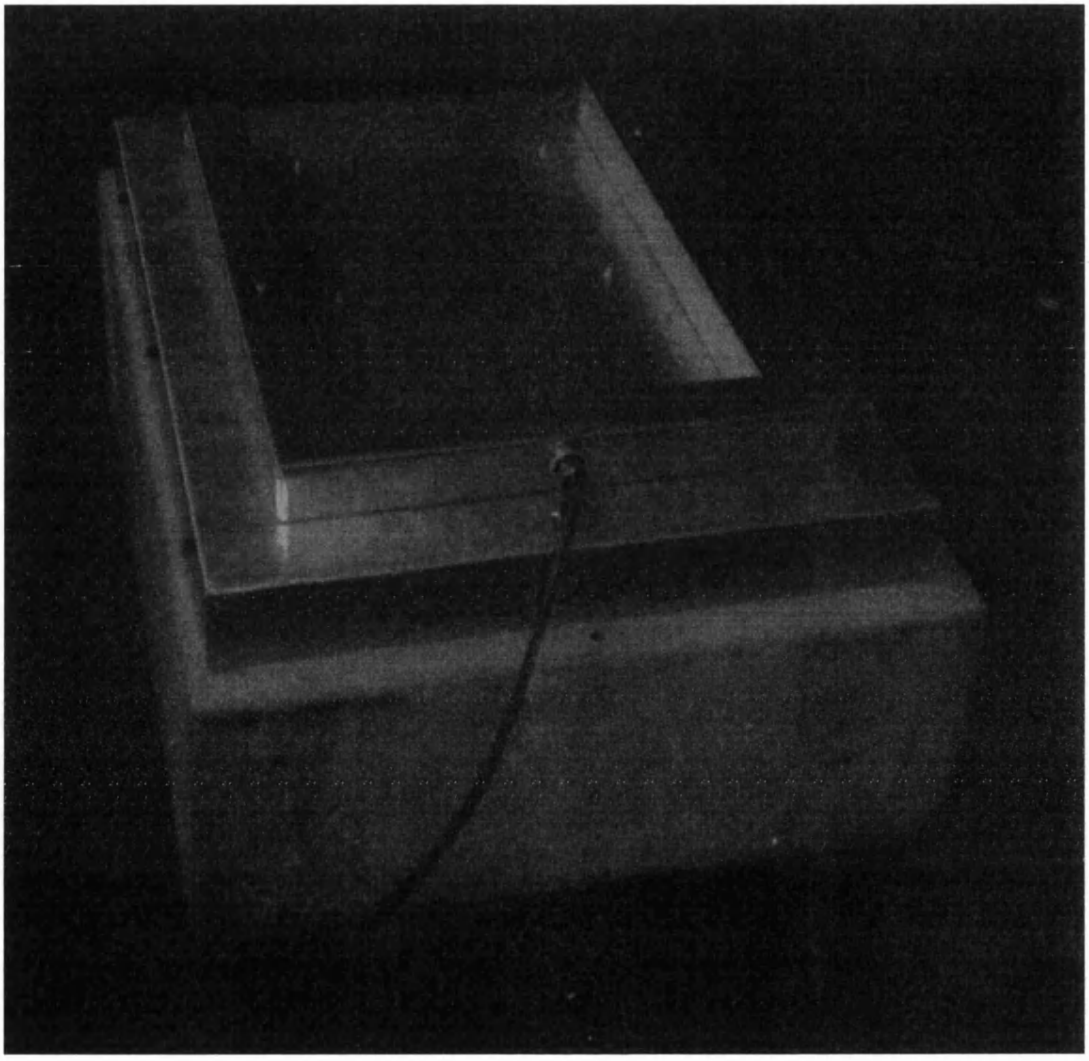
system utilised a combined volt and ammeter, AP80733 that enabled the heat output to be set up at a rate suitable to heat up the inside of the waste container within a reasonable timeframe. Commissioning trials using thermocouples were conducted using a Time Electronics Thermocouple Simulator/Calibrator, 1088, to determine the most appropriate settings. Figure 3.1k shows lamp arrangement and how the heating hood fits on the container. Thermocouples would be inserted through small holes drilled from each side of the waste container to control the heating trials and collect data.

FIGURE 3.1k: POLYMER VOLUME REDUCTION TRIAL EQUIPMENT

Heat Lamps in Cover

FIGURE 3.1k (Continued)

Cover on waste liner



3.1.2 Objectives

The aim of this initial work was to gain familiarity with the blasting equipment and assess the process capability for cleaning metallic radioactive waste. It was considered that the full extent of the process capability initially needed to be ascertained, and there would be no benefit in trying to clean waste material in a less aggressive manner unless it involved tooling or equipment for reuse. Therefore studies centred on evaluating the process using the most abrasive Silver medium [57]. Some non-abrasive Green medium [56] trials were undertaken because there is a possibility that some contaminated material or equipment could be reused or recycled, rather than disposed as waste, if the surfaces can be cleaned without imparting any damage. The initial trials aimed to characterise the blasting effects at full blast pressures (again nothing is gained by only partially cleaning any waste item), looking at blast trajectory and stand off and the effect on material removal rates and coverage. This would be achieved using inactive examples of metals that typically represent the waste that arises in the WAHF.

Secondly, the potential recycling of the medium was studied to confirm supplier claims regarding the economics of the process. In terms of its nuclear use for cleaning radioactive waste it must be demonstrated that the volume of secondary spent medium waste is significantly less than the volume of waste being cleaned or decontaminated. As part of this trial samples will be taken to examine media behaviour and deterioration during blasting and recycling cycles.

Thirdly, the media must be disposed of in a manner that is compatible with the remote handling capability of the WAHF. Therefore polymer volume reduction trials will aim to characterise the polyurethane polymers involved, and study their behaviour under radiation and heating conditions in order to propose potential packaging systems to facilitate waste disposal.

Ultimately the objective of these initial trials is to provide data and information that will support the next stage of study, and the development of active trials providing confidence in the ability of the process to do the task of radioactive waste decontamination.

3.1.3 Initial Trial Design

Generally the trials were designed to follow two parallel lines of investigation: first decontamination using polymer foam or sponge media materials, and second volume reduction of the polymer arising from the process. In each area materials sampling would be undertaken before, during and after inactive trials. Initial as-received sample material would be taken for characterisation studies. Sampling during and after the trials will enable studies to examine the changes in the characteristics of the materials involved.

Initial Blasting Trials for Decontamination

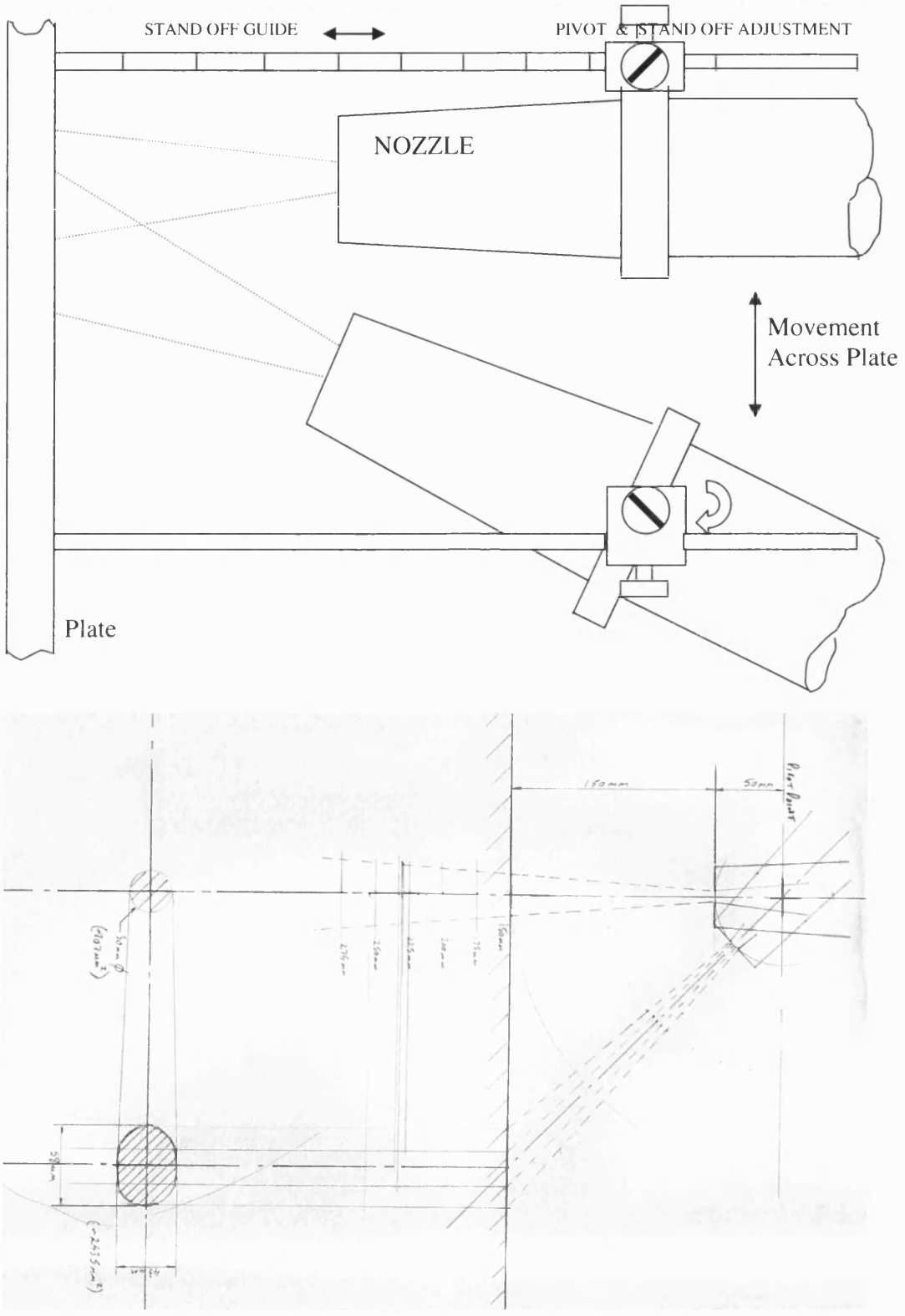
Figure 3.1a-f shows the sponge blasting system used in the inactive trials. In order to evaluate the deployment of the system for remote in-cave operation it would be necessary to test the process to determine if it is sensitive to blast nozzle stand-off and trajectory, medium recycle-ability and flexibility in cleaning different materials and surfaces.

In order to assess the effects of stand off and trajectory a measurement guide was fitted to the nozzle. This guide not only adjusted to give variable stand off, but also swivelled to enable different trajectories and stand off to be held when blasting the surfaces of plate metal. Figure 3.11 describes this design.

The stand off and trajectory angle can be set up prior to each run across the plate, which is clamped in a vertical position. The tracks of the blast paths can then be measured, and samples taken for testing and further examination. Measurements were taken of track widths against stand off distance. Samples were taken and surface roughness measurements, hardness tests and thickness measurements carried out, to correlate the process performance at maximum blasting conditions using new medium. Metallographic sections were taken to examine metal damage, removal profile and any medium interaction or adhesion.

In addition further blasting was undertaken by recycling the medium and taking samples of the medium after each pass. Blast periods were measured and medium losses through the grading process were evaluated. The medium was examined using optical macroscopes and microscopes, and scanning electron microscopes to study and characterise its deterioration from as-new to spent medium with each pass or cycle of blasting and grading. Particles of re-useable and spent fines were examined, measured and weighed.

FIGURE 3.1l: BLAST NOZZLE AND PIVOT STAND-OFF ARRANGEMENT



View showing how the blast footprint may change with trajectory

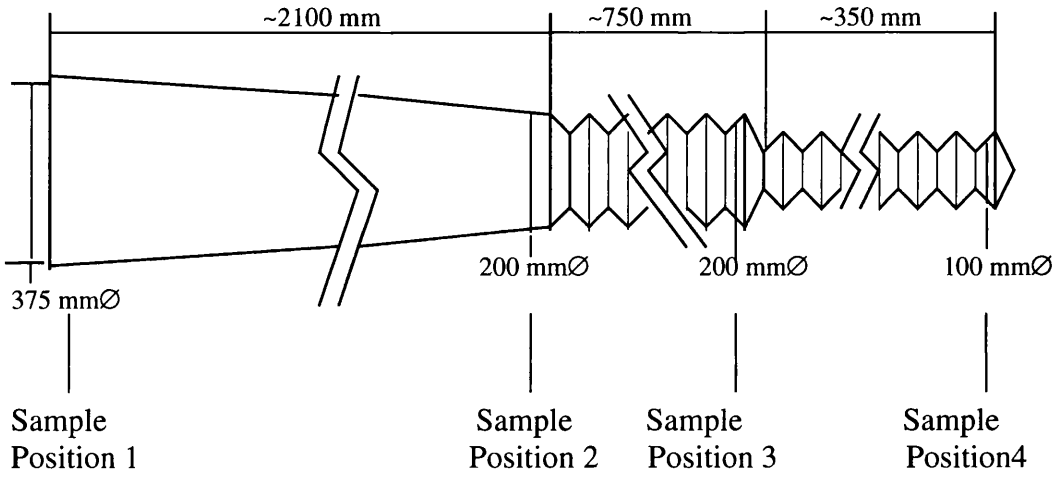
Initial Volume Reduction Trials

Firstly the gaiter and sponge medium was sampled in order to carry out polymer characterisation and information about their properties and behaviour, particularly with respect to the re-heating process they will undergo. Supplier information was limited to material data sheets [20, 56, 57].

Gaiter Materials

A complete gaiter (unused) was made available for initial trial work and sampling for detailed examinations. The gaiter consists of two lower corrugated sections and a tapered upper sheet section. Figure 3.1m describes the gaiter and the sampling positions, while Table 3.1c summarises all samples taken and the examinations conducted. Samples of gaiter material were removed reflecting the potential variations in manufacture. Four samples were taken from each position; one sample for as received examinations and three samples for examinations in to radiation damage effects. All samples were cleaned with water and dried (with tissue), then stored in sealed aluminium cans.

FIGURE 3.1m: GAITER SAMPLING POSITIONS



Four samples were taken from each position and labelled Au1 to 4 (unirradiated), A1to 4, B1 to 4, and C1 to 4 (to be subject to increasing doses of γ radiation). Each sample was cleaned using water and then placed into sealed aluminium cans identified by the sample code. Sample cans for irradiation were grouped by letter (indicating the level of irradiation to be received) and placed within another larger aluminium can and sealed. Samples A1 to A4 will be irradiated for ~60 days, samples B1 to B4 for ~120 days and samples C1 to C4 for ~180 days. All three batches of samples were then placed and sealed within a large paint tin to prevent contamination access to the inner sample cans during storage in-cave within a radiation field that is representative of the working environment of actual gaiters used in the WAHF. Figure 3.1n shows the position of the canned samples with respect to the fuel pin store.

The commissioning trials for the heat treatment rig arrived at voltages and current that gave temperature-ramp rates to achieve target soak temperatures within a reasonable period. At 10 A and 142 V the waste liner atmosphere achieved a temperature of 100 °C in one hour. It was necessary to manually throttle the volt/amp control once the desired temperature was approached to avoid over run. Trials would provide a soak temperature of up to 10 minutes for target temperatures of 60 °C, 70 °C, 80 °C, 90 °C, 100 °C, 110 °C, 120°C, and 130°C. Trials would firstly be conducted on small samples of both sheet gaiter from positions 1 and 2, and then corrugated gaiter from positions 3 and 4 (see Figure 4.1 n).

TABLE 3.1c: GAITER MATERIAL SAMPLING AND EXPERIMENTAL SUMMARY

Sampling Position			**Radiation**	**Planned Examinations**			
Description	Area Id.	Sample Id.*	(months)**	DSC***	IRS***	Weight Loss	Vol. Red.
TOP/SHOULDER	1	A_u	N/A	√	√	√	√
~750mm dia. tube from sheet		A	2	√	√	√	
PU tapering down over		B	4	√	√	√	
~2100mm to Mid. arm		C	6	√	√	√	
MIDDLE ARM	2	A_u	N/A	√	√	√	√
~250mm dia. tube from sheet		A	2	√	√	√	
PU tapering from shoulder just		B	4	√	√	√	
before join to corrugated elbow		C	6	√	√	√	
ELBOW	3	A_u	N/A	√	√	√	√
from corrugated PU tube ~120		A	2	√	√	√	
to 170mm dia. tube length is		B	4	√	√	√	
~750mm to wrist section		C	6	√	√	√	
WRIST/CUFF	4	A_u	N/A	√	√	√	√
from corrugated PU tube ~110		A	2	√	√	√	
to 135mm dia. tube length is		B	4	√	√	√	
~350mm .		C	6	√	√	√	

* A_u represents the unirradiated sample all the other samples were placed within a radiation field representative of the gamma dose conditions the material would recieve in service and storage for disposal.

** Samples were removed from the radiation field after 2, 4 and 6 months respectively for each sampling point

*** DSC means Differential Scanning Calorimetry and IRS means Infra – Red Spectrometry

Sponge Media Materials

Table 3.1d summarises the samples taken from the decontamination medium and the examinations conducted. The recycled and waste/spent media was sampled during blasting trials in order to assist characterisation of the material for eventual disposal. Recycling would only involve the abrasive Silver medium, therefore only as new Green medium was sampled. It is envisaged that non-abrasive cleaning using Green medium will not involve waste, but may be confined to cleaning tools and equipment for reuse. In these circumstances the economics are completely different to waste cleaning, depending more on the specific replacement and life expectancy value of the tooling or equipment being cleaned. This can only be evaluated on a case by case basis, nevertheless it is not likely that the Green medium will need to be used to full extent.

Both the gaiter and sponge medium samples were characterised primarily using differential scanning calorimetry (DSC – TA Instruments model 2910), and infra-red spectroscopy (IRS – Perkin Elmer Fourier Infra-Red Spectrometer model 1720X) techniques although weight loss measurement was also carried out. These techniques will help identify more closely the molecular structure and the thermal properties and behaviour of the material. Both materials were tested in heat treatment trials for volume reduction. Initial heat treatment would centre on the prospect of the polymer melting or plastic flow under a heating temperature sufficient to raise the material above its glass transition temperature. This offers the best opportunity to develop a test rig for use in-cave at the WAHF, since little mechanical or moving plant is needed. This in turn means less to go wrong and therefore less maintenance and potential dose uptake to operators. Should this not prove feasible it is expected that a simple compression moulding system might be used to its full extent.

TABLE 3.1d: SPONGE MEDIA MATERIAL SAMPLING AND EXPERIMENTAL SUMMARY

Sponge Type	Samples			Examinations				
	As-New	Recycled *	Waste**	Visual/macro	IRS	Metallography	SEM	Vol. Red.
Abrasive	√	√	√	√	-	√	√	√
Non-Abrasive	√	-	-	√	√	√	√	√

* The recycled medium is key to the economics of carrying out waste decontamination therefore samples have been taken from abrasive medium re-use only since non-abrasive cleaning of waste is unlikely to be successful in oxide, paint or ingrained substrate contamination removal.

** Waste samples are effectively the fines discarded from the recycling process.

DSC is a thermal analysis technique used to monitor the heat evolved or absorbed during exothermic or endothermic transformations in a sample [77, 78]. A typical analysis involves placing the sample and a reference in two chambers of a calorimeter that is steadily raised in temperature. The variation in thermal behaviour between the sample and the reference are recorded, and a plot of heat flow (m Js^{-1}) against temperature is produced. Features of these graphs indicate key properties of the polyurethane samples, such as glass transition temperature and specific heat capacity.

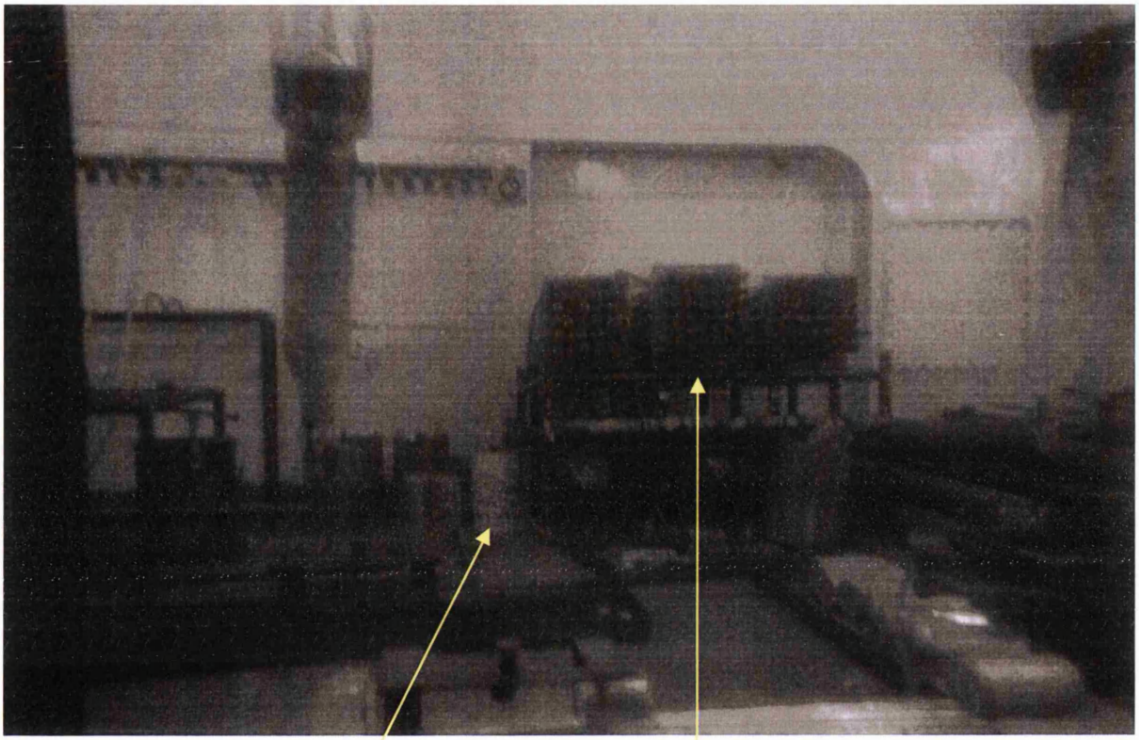
IRS is an analytical technique that can be used to detect the type and quantity of chemical bonds [58, 78]. This technique uses the characteristic that certain chemical bonds resonate and absorb infra-red radiation energy at specific wavelengths. Where the infra-red radiation wavelength spectrum is measured when passed through a film of the polyurethane, variations in the absorption at different wavelengths will indicate the type and degree of certain chemical bonding within the polyurethane. Also, absorption by a particular bond is sensitive to the local environment (such as nearby bonds, atoms, molecules and functional groups) so IRS can provide information on these aspects of structure and composition as well as on the bonds themselves..

To measure weight loss the polyurethane samples was placed in an oven for a period of time, and their weight before heating was compared with their weight after heating to calculate their weight loss.

If the sponge blasting technique is to be used as a practical decontamination technique the issues raised in dealing with the secondary sponge waste arising from the cleaning of

radioactive waste will need to be addressed. This work aims at going some way toward achieving this aim.

FIGURE 3.1n: POLYURETHANE SAMPLE IN-CAVE STORAGE POSITION



3.2 LOW LEVEL WASTE (LLW) TRIALS

Subject to the results of the initial blasting trials showing promise and confirmation of the supplier's promotional claims, it is necessary to test the Sponge-jet process in an actual radioactive trial. It is therefore necessary to design an experimental system within which trials could be undertaken on contaminated radioactive waste material. Suitable radioactive waste materials were therefore selected for the trials and an appropriate testing and sampling methodology developed. This section describes the equipment involved, what objectives were set and the trial design.

3.2.1 EQUIPMENT DESCRIPTION

Low Level Waste Blasting Trials

The same blasting system used in the initial trials was moved in to the radioactively controlled area for the Low Level Waste trials, including the media grader. The additional equipment used is summarised in Table 3.2a. Much of this equipment is of bespoke design, in that it was designed for these specific trials within the constraints of the WAHF plant and equipment. Specific aspects of the new LLW system design will be described in turn, and equipment taken from the initial trials is described in Section 3.1.1.

The containment required to undertake radioactive blasting trials needed to be of a significantly higher standard if the trial is to get approval through the Site Safety Management System. A wooden enclosure was designed with roof and side door access and egress.

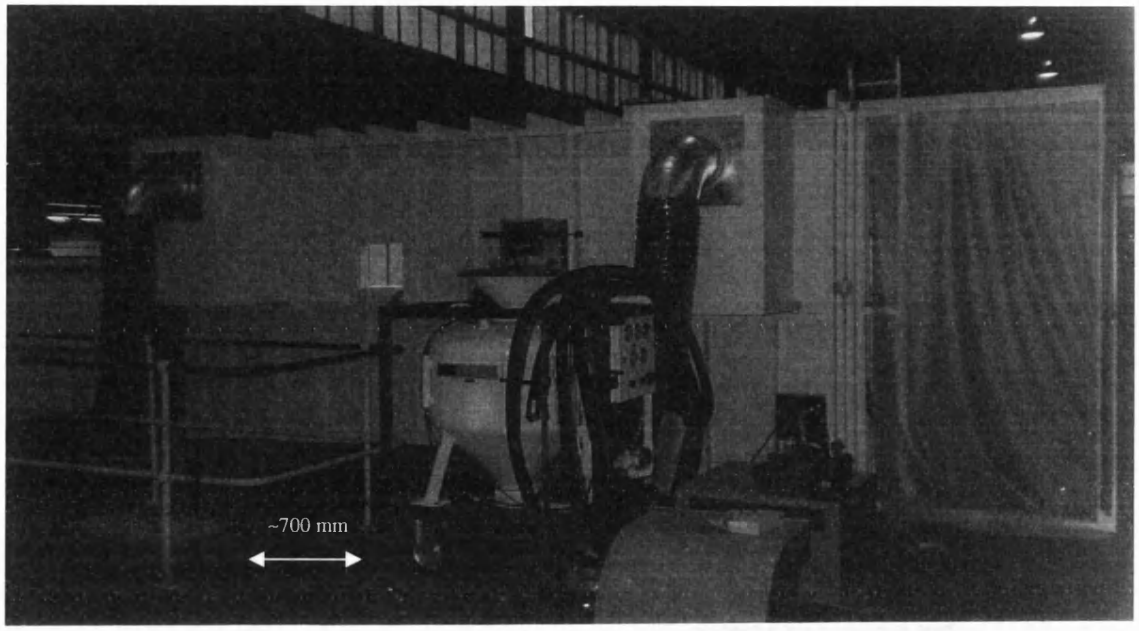
TABLE 3.2a: DETAILS OF EQUIPMENT AND MATERIALS USED IN THE LLW TRIALS

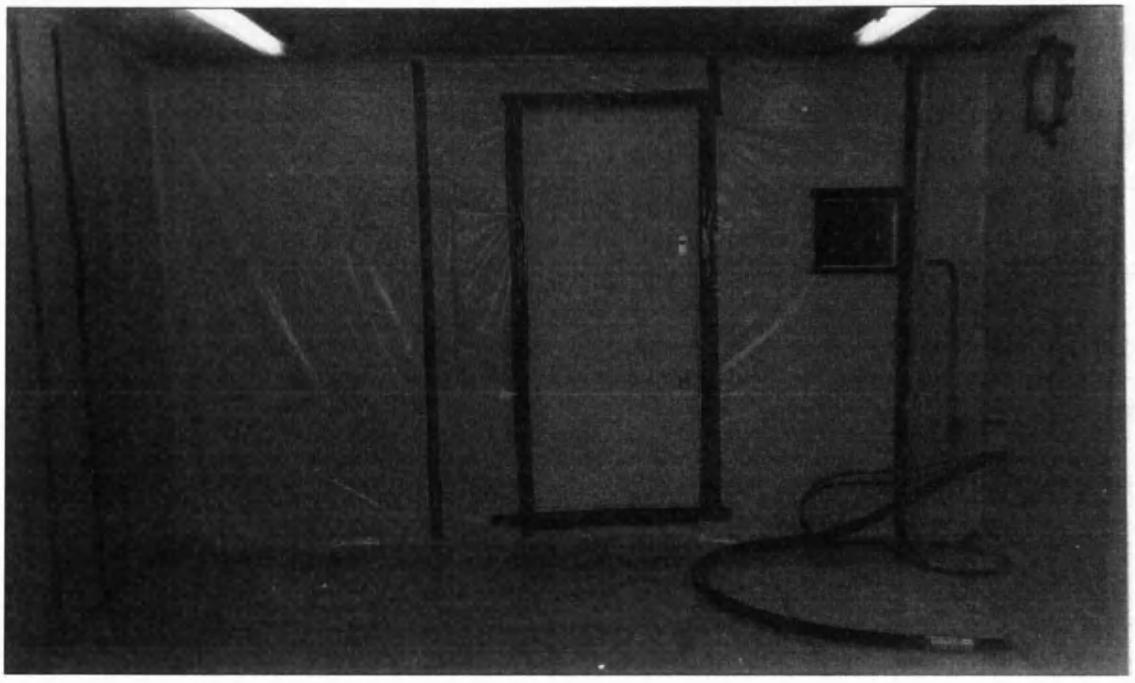
Equipment / Materials	Description
Sponge-jet Blasting System	240 Litre Feed Unit
Compressor	After cooled capable of delivering $6m^3$ of oil-free air at 0.7 MPa
Media Grading System	Pneumatic drive vibration on inclined two stage wire mesh bed
Silver sponge medium	Polyurethane foam particles containing abrasive aluminium oxide grit (bulk density ~535 $Kg.m^{-3}$)
Green sponge medium	Polyurethane foam particles only
Personal Protective Equipment (PPE inc Radiological PPE)	Integral dust mask and visor, gloves, ear defenders, overalls and protective apron, full PVC suite, radiological monitoring and dosimetry equipment
Collection and Sampling Equipment	Dust pan and brush, collection bags, sample containers
Blast containment and extraction system	Modular shed of inside dimensions 4.0m(L) x 3.25m(W) x 2.4m(H) with side windows for external supervision, roof access for crane(loading waste or equipment), and barrier access for contamination control and man entry. Extract lines to the Cave system, services for lighting, blasting lines, control lines and airborne monitoring.
Air sampler	This is used to extract air from the shed during the trial and collect active particulate
Crane Girders (two cut up sections)	Girder 1: ~1.3m x 0.46m x 0.4m = $0.24m^3$ Girder 2: ~1.3m x o.4m x 0.8m = $0.46m^3$
Three redundant flask posting port stations	Effectively 7.6 te steel cylinders.
In-cave machine tool	Large tool adapted for remote in-cave operation used for machining specimens from fuel assemblies and requires refurbishment

The containment system was an engineered wooden structure that had hermetically sealed joints through the use of double silicon sealant runs (inside and out), vacuum tape (inside and out) and the whole of the inside walls, floor and ceiling were covered with a PVC membrane. This enclosure was built on the cave 2, roof area (see Figure 3.2a).

FIGURE 3.2a: LLW TRIALS ENCLOSURE

Access on right with service port for blast system below right baffle box. Ventilation ducting from each end of the enclosure leads to the cave inlets on the floor below. Window and inlet filter in the middle of the side wall.





View inside the enclosure looking toward access door, with service port on lower right featuring blast hose, dead mans handle control and dual sampling and smoke injection point.

The ventilation of this containment system during the LLW trials utilises the building cave extract system through connections to cave 1 and 2 via 300 mm dia. ducting attached to the east and west inlet filter housings. The caves are each extracted at a normal rate of between 19 and 23 m^3 min^{-1} with the capacity to temporarily increase flows to ~38 m^3 min^{-1} should operations require improved containment. Cave inlet filters were temporarily removed from these housings and stored. New inlet filters were fitted to the enclosure walls to effectively provide an extension of the cave containment to the enclosure area. This will have the following benefits:

- volume flow rate to cave only on demand and at a velocity of just under 0.5 ms^{-1} for maximum blasting at $4m^3$ min^{-1}, dissipated between two caves and not one, minimising any potential disturbance to the cave extract system,

- inlet filters on the enclosure negate the need for sealed containment working (and therefore specialised breathing apparatus), any potential egress of air to the cave roof atmosphere outside the enclosure would be filtered,

- cave shielding is not compromised, and filtered containment is retained.

The completed system was smoke tested to prove the containment integrity. The smoke trial included a demonstration of inward flow to cave during access and egress, filling the enclosure full of smoke and clearing it through the compressed air injection line. This air injection not only simulates and proves the contamination movement from a blast trial will go into the cave and therefore be safely abated by the building filtration, but also indicates the fresh air injection time required to clear the enclosure prior to access/egress

after the blasting trial. This therefore ensures that any risks of any airborne radioactive contamination being released from the enclosure are minimised.

Local beta-in-air monitors (measuring beta radiation from any potential aerial contamination) were employed at both the cave roof and at the cave 1 and 2 operations area to detect any potential airborne release of radioactive contamination. These monitors take air samples around the cave roof enclosure and in the operating areas outside caves 1 and 2 to warn of any loss of containment. An air sampler was also fitted to a pipe that draws air from inside the enclosure during blasting to collect a sample/measure of the airborne contamination generated during the trial. Further to this there are routine radiological monitoring surveys of the cave roof area which would immediately indicate any leakage from the enclosure.

In order to ensure that the cave depression is not compromised the extract fans on caves 1 and 2 were increased by between 10 and 15 % of capacity to accommodate the additional $4m^3\ min^{-1}$ from blasting, giving a safety factor of at least 2.

Figure 3.2b describes the layout of the LLW trial equipment and enclosure system that was designed to contain the low active waste blasting trials. The floors and wall sides have been shielded by plate metal to firstly protect the enclosure but to also afford some shielding from radiation emanating from elsewhere in the cave roof area. This helped to ensure that when assessing the radiation from contamination on the samples, monitoring only detected radiation from samples within the enclosure. This is particularly important when trying to detect very low levels of contamination.

FIGURE 3.2b: SCHEMATIC LAYOUT OF THE LOW LEVEL WASTE DECONTAMINATION EQUIPMENT

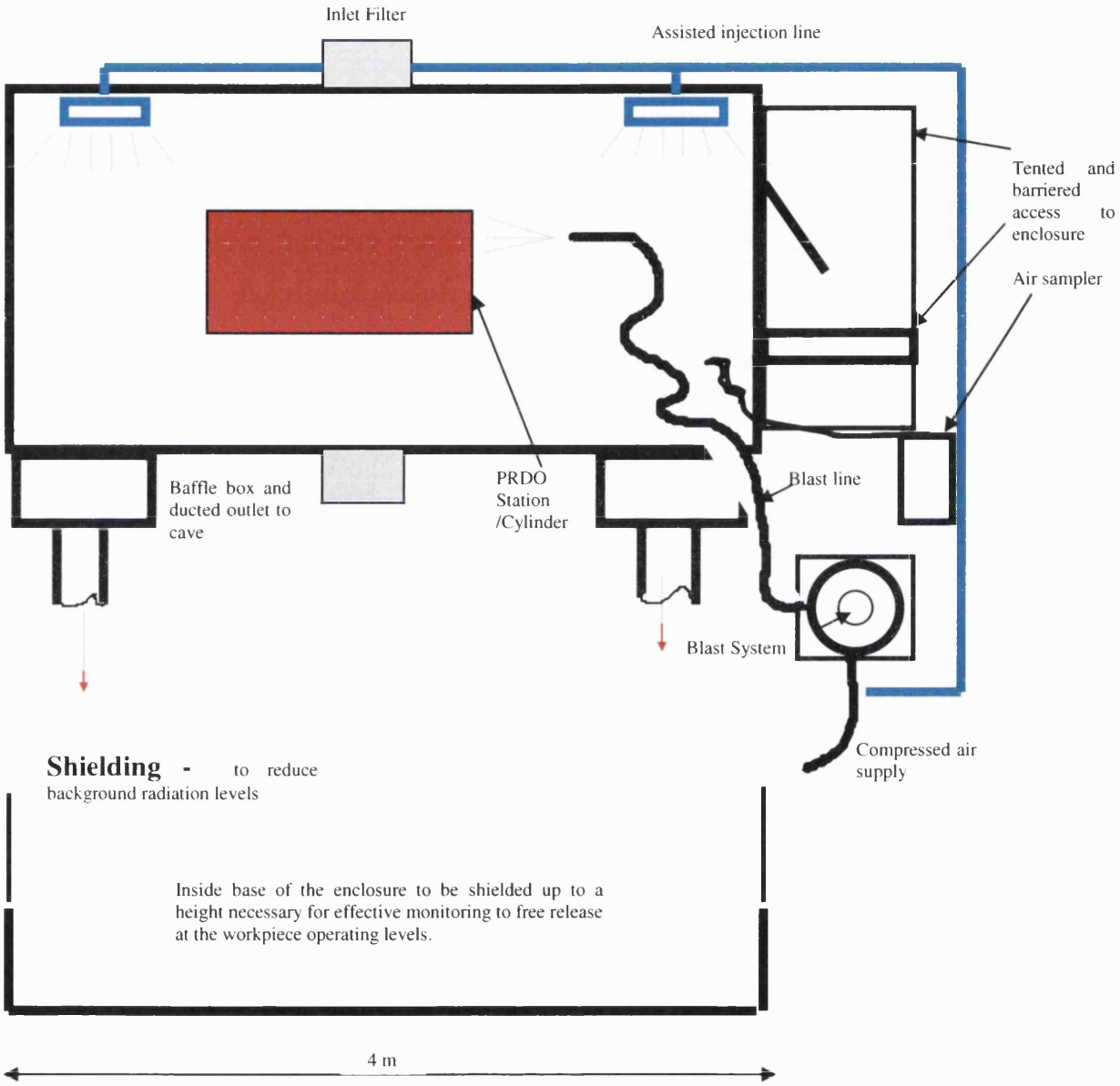
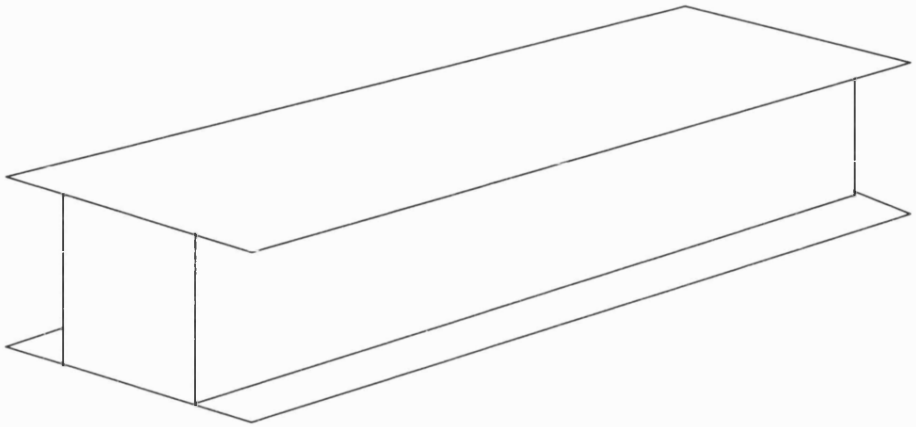
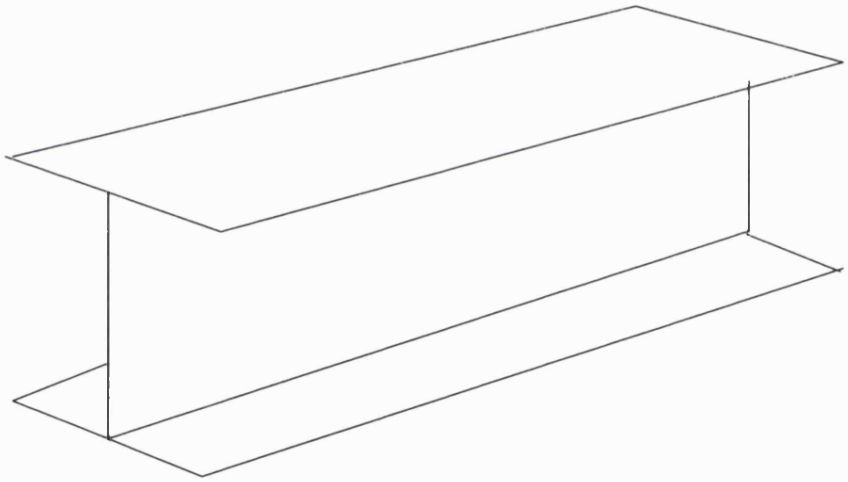


FIGURE 3.2c: LLW STEEL GIRDERS USED AS TRIALS SPECIMENS

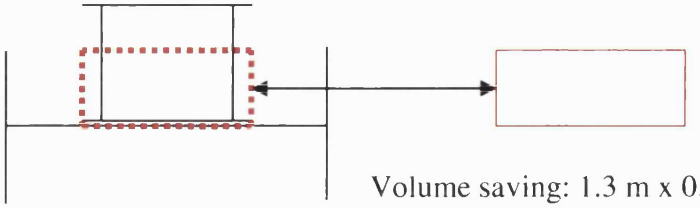


Girder 1 dimensions - ~1.3 m (long) x 0.46 m (wide) x 0.4 m (high) = 0.24 m^3



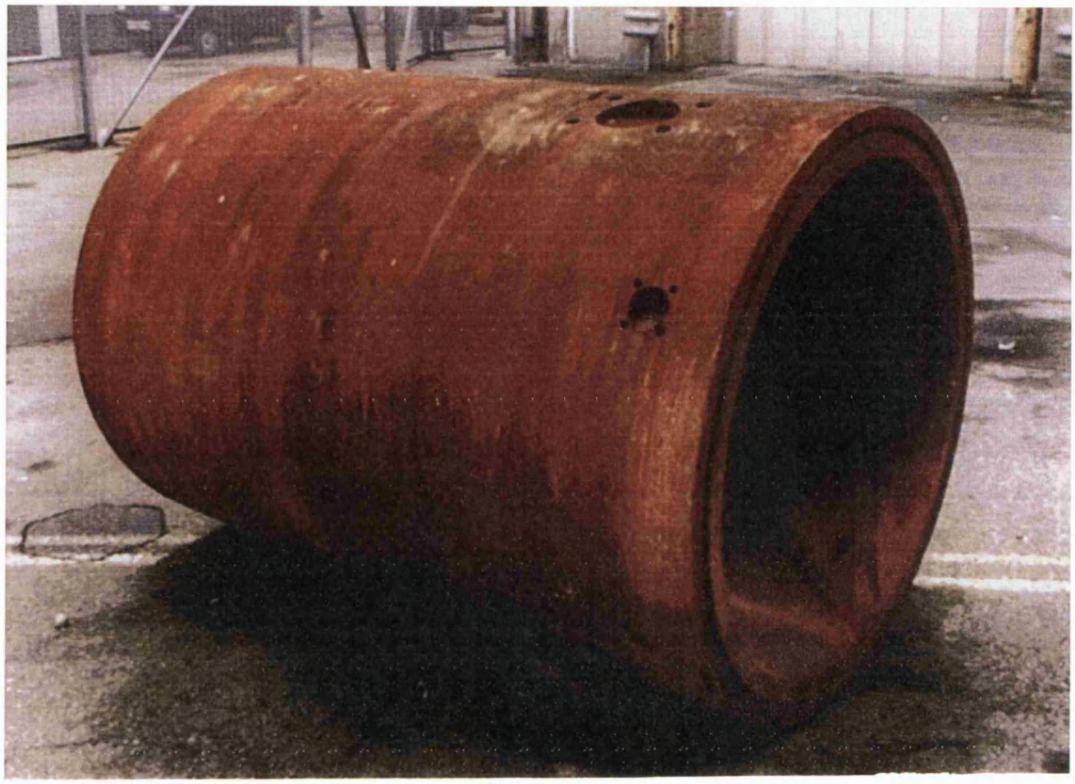
Girder 2 dimensions - ~1.3 m (long) x 0.4 m (wide) x 0.8 m (high) = 0.42 m^3

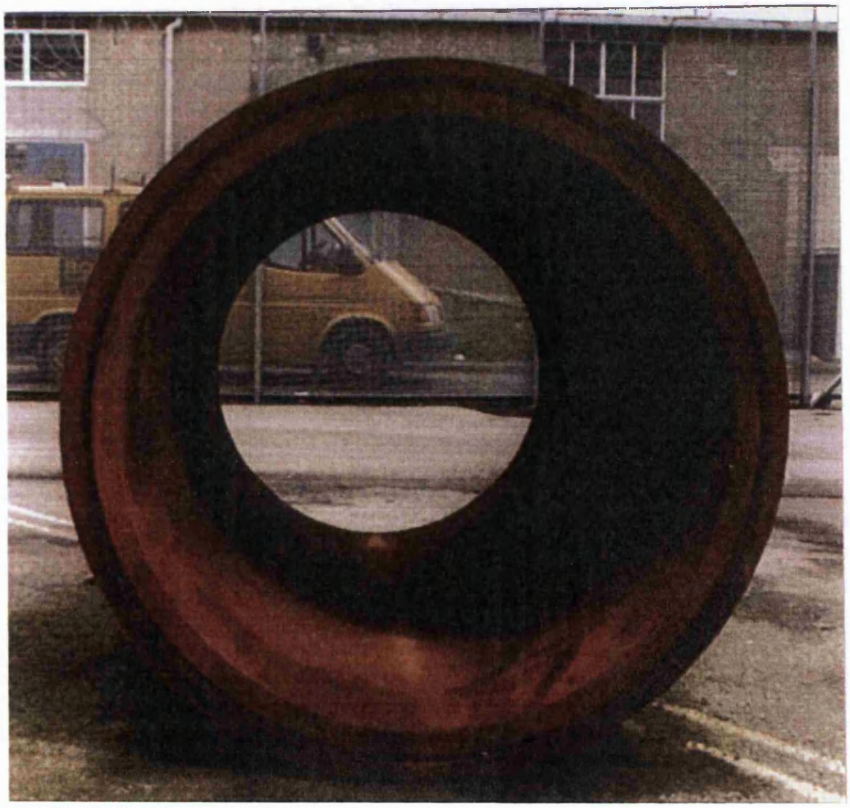
Possible packing



Volume saving: 1.3 m x 0.46 m x 0.2 m = 0.11 m^3
(Total Surface Area: ~8.63 m^2)

FIGURE 3.2d: LOW LEVEL WASTE STEEL CYLINDERS USED AS TRIALS SPECIMENS





Redundant Flask Station (1.83 m(L) x 1.32 m(O/D), and 0.15 m wall)

Two sections of crane girder and three large cast steel (low alloy) cylinders from decommissioned flask posting stations were initially suggested as subjects for LLW decontamination trials (see Figure 3.2c and d). The WAHF building crane had been replaced and the gantry was cut up for ease of packing for disposal. The overhead crane had not been contaminated during its lifetime even though it operated within an active area. Nevertheless this represented a large volume for LLW disposal to Drigg, because all the steel work was heavily painted and it could not be assumed that there was no contamination entrained within the paint. Two sections were selected for a decontamination case study using the Sponge-jet system.

The dimensions of the flask station cylinders are 1.83 m(L) x 1.32 m(O/D), and a wall thickness of 0.15 m. They have a total surface area to be cleaned of ~44 m^2 (14.55 m^2 each). They weigh 7.6 te each and would occupy an in-situ grouted volume in the LLW repository at Drigg of ~27 m^3, assuming a 300 mm overpack (e.g. 2.43 m x 1.92 m x 1.92 m x 3). This is likely to be the preferred disposal route for large solid items such as these, since packing with other waste in ISO freights (freight containers design to International Standards Organisation standards) may require large volumes of low density material to pack around each cylinder in order to fully utilise the ullage space remaining within the freight package. Each cylinder occupies ~2.5 m^3 net volume (including bore volume). The WAHF usually handles half height ISO freights but the internal height of these disposal containers is 1.104 m which precludes disposal of these cylinders without substantial effort being expended in cutting them up. The next size of ISO freight is a two-thirds height ISO freight, which provides for wastes with a height dimension of 1.552 m. The transport of these ISO freights is also subject to 30 te gross loaded weight limit. With a net volume for all three cylinders occupying <30 % of the total gross ISO freight

volume (also ~27 m^3), and nearly 80 % of the transport weight limit, it is unlikely that the WAHF operations will generate sufficient waste to take up the potentially unused ullage space within the ISO freight. So either way the cylinders would otherwise be disposed as LLW occupying the best part of 27 m^3.

The non-abrasive medium will be tested on a machine tool (vertical milling machine) removed from the cave system and considered as a case study investigation into the ability of the process to decontaminate equipment for refurbishment and re-use (including savings in dose uptake or increased working times), rather than direct disposal and replacement.

PU Volume Reduction

The effect of radiation damage on PU must be considered particularly for the properties of interest under active processing conditions. Since the effects of radiation can cause profound changes to the properties of many engineering materials, it will eventually be necessary to carry out a full-scale active trial. This will require a full safety case approval from the Windscale safety management. Therefore inactive and low active trial data will help provide robust support to such a safety case, and assist the implementation of more highly active trial studies later on.

In service radiation damage to the gaiters, coupled with prolonged storage in contaminated environments, will cause changes to the structure of the PU material. This in turn could cause adverse variations in the way the PU behaves when heated. Therefore the evaluation of PU that has seen active service is important, because its performance will directly influence the successful application of any volume reduction process.

Unfortunately all waste gaiters are highly contaminated preventing their use for low active trials. An alternative strategy has been adopted where sampled PU gaiter material (see Figure 3.1m) has been packaged in sealed containers, and placed within a radiation field for given periods of time to represent typical service life in cave (see Table 3.1d and Figure 3.2d). The samples were removed from the radiation field and assessed in a similar manner to the as receive PU materials.

PU sponge medium will be assessed in a similar manner should the decontamination trials prove to be successful.

3.2.2 Low Level Waste Trial Objectives

The objectives of the LLW trials from the point of view of this project are to evaluate the performance of the blasting process to decontaminate waste and develop the basis of a trial design for higher radioactive trial. The volume reduction of PU will concentrate on examining changes in material characteristics under irradiation and the implications for volume reduction.

Blasting Trials

The main objectives of this work are to;

- test the cave ventilation system's ability to cope with the volumetric flow from the blasting process,
- examine how the process media and materials interact to decontaminate surfaces (both abrasive and non-abrasive),
- examine how the sponge material behaves during successive recycling,

- study the airborne contamination levels arising from the process,
- obtain data on the performance of the process to decontaminate metal,
- obtain data on the cost-benefit of the overall process,

PU Volume Reduction

The main objectives of this work are to;

- produce PU samples that are representative of PU that will be generated as radioactive waste,
- examine and characterise the material properties of the radiation damaged PU,
- establish an approach to volume reduction that could be adopted for minimising the sponge waste arising from the sponge blasting decontamination process.

3.2.3 Low Level Waste Trial Design

The whole design of this stage of the project has to take account of the increasing radiological hazards. It should therefore be born in mind that the trials and development of experimental apparatus need to take account of the requirements of radiological protection primarily for the operators doing the work, but also for other workers in the building and for the wider public and environment. These additional considerations have consumed substantial effort in effectively designing the test rigs or systems necessary to carry out the trials.

Low Level Waste Blasting Trials for Decontamination

Initially the girders would be stripped of paint to leave only exposed metal surfaces that can be monitored to obtain an unequivocal measure of the activity on the steel. The use of media will be evaluated to establish the economics of stripping such material, because much nuclear waste will be coated in this manner. It has been common practice in the past to fix contaminants with strippable coatings to protect the underlying material from contamination. This would provide evidence that this technique could be viable for such material, enabling its reuse.

The active trial will use three PRDO flask stations, which are effectively large steel tubes or cylinders from decommissioned flask posting ports. Fuel elements will have been transferred from the flasks into the cave below through these tubes. Consequently contamination will collect, particularly on the ends and inner surface of the tubes, otherwise making this material low level radioactive waste (>0.37 Bq g^{-1}). The steel cylinders are ~1.32 m in diameter (O/D) and ~1.83 m long with a ~0.15 m wall thickness. The outer surfaces were painted and the inner surfaces machined with varying degrees of corrosion. The ends were the most contaminated and had the worst corrosion.

The containment system was developed, commissioned and approved prior to decontamination operations.

The blasting system operates using a compressed air supply of ~6.2 m^3 min^{-1} at 689 kPa (220 ft^3 min^{-1} and 100 lbf in^{-2} respectively, as specified by Sponge-jet). The compressor and Sponge-jet system operated during the trials at ambient atmospheric conditions. The WAHFs are very close to sea level such that the system takes air at or just above

atmospheric pressure (101.3 kPa), and temperature will vary between 20 and 25 °C. The compressor used for the trials was capable of adjustment to take account of these variables. The compressed air supply is required initially to overcome system friction and inertia on start up and subsequently to operate and maintain air motors running the mechanical feed, vibrators, stir jet and pressurise the media supply vessel, as well as delivering up to ~4.1 m^3 min^{-1} at 483 kPa for actual blasting operations (see Figure 3.1e). The pressure vessel and main controls stand outside the enclosure next to the tented access area, the blast and control lines are fed into the enclosure through a service panel in the wall of the enclosure. The service panel also supports a smoke injector point for testing containment integrity during commissioning trials, and then doubling as a beta-in-air sampling point during the actual blasting operations in order to sample the enclosure atmosphere during the blasting operation. A compressed air line will provide clean air to flush contaminated air through into cave following the LLW active trials on the steel girders and cylinders and prior to access/egress to the enclosure.

The containment is designed such that the path of least resistance ensures the blast air (4.1 m^3 min^{-1}) flows directly into the cave 1 and 2 and is then captured by the in-cave ventilation system. This equates to a mean flow velocity of ~0.48 m s^{-1} through the ducts and into each inlet manifold duct where the increased duct size will cause the mean flow velocities to drop substantially before entering cave 1 and 2 respectively. This discharge is into a total cave volume of ~200 m^3, which is itself being extracted at a rate of more than 38 m^3 min^{-1} (~0.64 m^3 s^{-1}), depending on filter conditions. The cave ventilation system was designed to provide at least six air changes per hour in the caves and ensure that the air velocities through any access or opening in the cave system is not less than 1 m s^{-1}. These conditions could be eroded by the introduction of air from this blast

process. This additional flow into the cave system is ~10 % of the cave 1 and 2 extract flow (under normal conditions). Since the ventilation system is operating at 50 % of the fan capacity the cave 1 and 2 fan speeds could be easily increased by up to 10 %, which in theory should increase the extract from the two caves to ~46 $m^3 min^{-1}$ (0.77 $m^3 s^{-1}$), and therefore retain the designed cave containment conditions. To ensure this is the case a great deal of emphasis was placed on the enclosure sealing arrangements during fabrication and the subsequent commissioning smoke trials.

A smoke generator was used to send small blasts of smoke up and across the outlets from the enclosure while the entrance door was ajar. The smoke was quickly drawn in to the ducting by the in-cave ventilation, and was effective at both outlets, demonstrating that there is no cross flow between caves via the enclosure. Smoke was injected into the sealed enclosure (entrance door closed) until visibility was down to less than a metre. All enclosure joints were inspected for any smoke loss and no leaks were observed. Smoke was puffed up the faces of both enclosure inlet filters showing slight take up into the filters with the enclosure door closed. The enclosure was left for 30 minutes with no significant signs of smoke/air movement or clearance suggesting the enclosure is an effective containment system. Within 10 minutes of the entrance door being opened carefully ajar the enclosure was fully cleared of smoke.

With the enclosure full of smoke, a dynamic trial was attempted where the building compressed air supply was released through the service panel into the enclosure. This is a 70 p.s.i. supply and estimated to provide at least 50 % (depending on losses and demand elsewhere from the two 175 c.f.m. plant compressors working in tandem) of the equivalent blast air volume (~75 c.f.m.). The cave fan speeds were not increased and no

smoke was observed at cave 1 or 2, throughout the short period it took to clear the enclosure. This lent some confidence that the cave containment would not be compromised during actual blasting operations. The trials were approved and permission to proceed was granted following submission of the results to the site Safety Management Committee.

The girders and cylinders were then loaded through the enclosure roof door and set on stillages in the centre of the enclosure ready for blasting trials. The girders were stripped first since they were considered to be essentially clean. Following that assessment the first clearly active trials would be conducted using the first redundant flask station. A specimen area on the first cylinder of one square metre was marked up and monitored to evaluate the radioactivity inventory of the test area prior to the blasting trial. This area would also be wiped by swab to obtain some idea of the level of loose and fixed contamination.

The blasting trial on the cylinder would commence initially by cleaning the one metre square area with a once over pass. This would be done manually by directing the blast nozzle across the one end and inner surface of the first cylinder in a careful overlapping raster pattern. This was achieved using two people (one directing the nozzle, the other controlling the dead-man's handle) dressed in full Radioactive Personal Protective Clothing (including PVC suites, dust-masks, rubber gloves and boots and dosimeters), who entered the enclosure to do the blasting, and one operator observing outside the enclosure (to assist in access and egress or in an emergency) with over-riding control of the blasting system. The test area was then re-monitored and swabbed to assess the radioactivity inventory of the cleaned or decontaminated surface.

During this initial LLW test trial the Beta in Air monitor was switched on so that it drew a representative sample of the enclosure air during blasting and fed it through a filter paper, which trapped any airborne contaminants raised from the test area of the specimen during the blasting trial. The radioactivity trapped could then be measured and related to the volume of air sampled and the volume of air generated during the trial.

The blasted medium was collected and samples taken to assess the general radioactivity content retained by the sponge. From this data it should be possible calculate a radioactivity contamination balance and assess the effectiveness of the process for a single pass of fresh medium.

The cylinders were then to be cleaned or decontaminated completely by recycling the medium as much as possible. All spent medium will be collected and the cylinders removed to low background areas to assess more accurately the surface contamination remaining, and whether the material could be disposed as 'clean' or non-radioactive material, possibly for re-cycling.

A non-abrasive decontamination trial was conducted following the cleaning of waste flask stations, on a milling machine. This would assess the benefits of using the Sponge-jet process to enable the reuse of tooling and equipment within the nuclear industry offsetting its early disposal and reducing operator dose uptake. There are different cost-benefits involved with the studies involved in these trials.

The trials will then be reviewed to see if there are lessons to learn. Samples of medium will be studied further and information fed-forward to the next stage of this project to examine how higher activity waste trials might be conducted.

Low Level Waste Volume Reduction Trials

Three samples of gaiter (taken from each position identified in Figure 3.1m) and sponge (both Green and Silver) medium described in Chapter 3.1 were each placed in screwed topped aluminium (~75 mm long by ~15 mm dia.) cans with seals, the lids were then sealed using vacuum tape which was wrapped around the lid to offer additional sealing. A set of samples from each of the positions identified in Chapter 3.1 were then collected into a larger screwed topped aluminium (~100 mm long by ~50 mm dia.), and sealed in a similar manner to the smaller cans. These three sets of samples were then put into a larger paint tin and the lid sealed. This arrangement would allow the polyurethane gaiter to be put into a suitably representative radiation field inside the cave system within the WAHF without contaminating the polyurethane samples themselves. Figure 3.1m shows the fuel storage racks, next to which the paint tins containing samples were stored. The paint tin was retrieved at predetermined intervals to remove a set of samples for examination. The inner cans and samples would be free of radioactive contamination and therefore could be handled in a non-active laboratory.

Each of the samples represented a different type of polyurethane that may need to be volume reduced, and a set of each were subject to a period in the radiation field of two months, four months and six months, respectively.

The level or rate of radiation experienced by the polyurethane samples will be the same until removed from the radiation field. The source of the radiation is Civil Advanced Gas-cooled Reactor (CAGR) fuel pins. The radiation will be in the form of a wide energy range of gamma radiation that easily penetrates the thin layers of metal representing the paint tin and aluminium can walls containing the polyurethane samples. While these samples will not become contaminated, and are therefore unaffected by alpha radiation, there is a possibility that there may be a small influence from the more penetrating beta radiation around the paint tin. This is expected to be a minor part of the ionising radiation effecting the samples. Gaiters used in cave operations will become both contaminated and exposed to both higher and lower gamma, beta and alpha radiation, depending on the cave they are used and the operations they perform. Clearly the gaiters on MSMs near the fuel store will receive higher absorbed doses in a shorter time scale from gamma radiation, while gaiters in the LLW and ILW waste processing caves will not receive such high gamma doses, but their contamination may be relatively high, leading to increased absorbed doses from alpha and beta radiation. Gaiters may become waste before failure due to a breakdown on the MSM, and therefore will need to be discarded to effect repairs. They may fail as a result of non-radiation influenced defects. In all cases the gaiter will be stored for long periods before disposal, and it will be difficult to predict the actual dose absorbed, and therefore the level of damage the polyurethane will be in by the time it is ready for processing for disposal. Nevertheless, it will be necessary to characterise the behaviour of polyurethane when damaged by radiation in order to have confidence in its performance in any future volume reduction process involving heat treatment, and following transfer for interim storage and ultimate disposal. These samples are designed to provide examples of polyurethane that represent gaiters that would be in a worst case state of radiation damage for in-cave volume reduction. Studies of this material will also

indicate how the volume reduced polyurethane wastes will deteriorate during interim storage and after final disposal.

The sampling and studies are to be carried out in line with that presented in Tables 3.1d and e.

3.3 HIGHER ACTIVITY TRIALS

Following the successful outcomes of earlier trials it would be necessary to develop a test rig that could simulate as close as possible the broad operation of the Sponge-jet process, as it would need to be installed in a cave within the WAHF if adopted. The previous trials must confirm that the Sponge-jet process has the potential to achieve effective cleaning of solid waste that is radioactively contaminated. The medium will need to be effectively recycled to realise the economic benefits of the process. In order for this decontamination process to be used in the WAHF a method of sponge media management will need to be proved and tested that does not diminish the performance of the process. A conceptual design for such a system has been proposed, a prototype test rig built and developed for inactive and radioactive trials to be undertaken to evaluate the interaction of the Sponge-jet process within such a remotely operated arrangement. This section briefly describes how these trials will be conducted.

3.3.1 Equipment Description

Where equipment has already been described in earlier chapters no further explanation will be provided except where expansion may be required to cover any adaptation or modification.

Higher Active Blasting Trials

Before any equipment could be specified a preliminary design was developed from the following basic requirements of the Sponge-jet process if it were to be deployed within a cave at the WAHF. These requirements could be listed as follows;

1. Remote control and operability, using MSMs and in-cave crane to load and unload waste and direct blast nozzle,
2. Independent ventilation to the cave system, to remove medium and contaminants from blast area, so as not to spread contamination around the cave. Also to prevent any diminishing effect on the cave ventilation and containment.
3. Media containment during blasting to prevent medium ricochet around the cave, that would require subsequent clean-up.
4. Media management to collect and separate blasted medium in to reusable and spent medium/fines to facilitate the realisation of automated recycling economics.
5. The media management system must minimise any carry over to the filters to prevent the economics of the process being eroded by additional waste filter volumes.

Figure 3.3a presents a flow diagram of conceptual operations involved in the operation of an in-cave Sponge-jet decontamination system. Figure 3.3b shows a schematic of how these operations might be arranged. Essentially a brainstorming exercise came up with a local containment system around the blast area which would be extracted at a rate that ensured the medium is removed with the air flow via a hopper arrangement below the blast zone. The air and medium would then be passed through a gravity settler to remove the larger reusable medium particles and then the air and finer waste particles would be removed from the airflow as it passes through a cyclone. High Efficiency Particulate in Air (HEPA) filtration would then abate very fine particles remaining in the air stream. The reusable and waste medium could be collected in shielded drum stations that can be

'hoovered' out to transfer the medium for either recycling, and reuse, or waste disposal as required. This conceptual design utilises a single extract system, which could operate in three stages. The first mode pulling blasted medium from the blast hood via the lower hopper to collect the medium into reusable and waste drums. The second mode switches the airflow to a line that pulls or 'hoovers' the reusable medium up to a cyclone that returns the medium to the blast system pressure vessel. Finally the extract would be switched to a line that draws waste medium/fines into a waste disposal drum where it could be heat treated, compacted, or transferred to another facility for further processing (e.g. super-compaction at BNFL) prior to final disposal. This could be achieved through an interlocked switching system at suitably designed manifold.

Much of this system is standard engineering design, but for the process to work the separation will need to be effective and the carry over to the filters is minimal. The gravity settler must not allow medium through to the cyclone or the recycling economics will be diminished dramatically as waste filter volumes are accrued. The sizing of these components are based on the approximate partition size given by the mechanical grader supplied by the manufacturers, and studied following the initial trials in to recycle-ability of the medium (see Section 4.1). These parameters and the blast air being delivered to the blast hood and the hood size were used to model the system and provide design parameters for the system components. This work is presented in Section 4.3 and provides a continuity to the results of the inactive trials on the system. Nevertheless the literature [79] suggests that differential settlers can remove particles from gases down to sizes in the region of ~10 μm diameter in some cases, although efficiencies diminish dramatically below 0.2 to 0.1 mm, whereas cyclones or centrifugal separators are efficient at removing particles from air streams down to 10 μm diameter, and can maintain

reasonable efficiencies down to 5 μm. Clearly the reusable medium will be in the order of millimetres across not microns, but the cyclone will need to be effective at removing fine material down to <10 μm in order to protect the filters from premature loading and adding to waste volumes. The filters are effective in capturing particles from ~5 μm down to 0.01 μm [77]. It was considered that this preliminary design may have the potential to provide adequate abatement of discharges to the environment, which will be an important prerequisite in meeting legislation and regulatory requirements as described in Chapter 2.2. It should be noted that the process involves the cold mechanical removal of contaminants and is not expected to generate sub-micron particles (e.g. aerosols etc) in any quantity. Prior assessment of the waste form to characterise its radioactive inventory would be required to demonstrate its suitability for processing/treatment using the Sponge-jet technology.

FIGURE 3.3a: FLOW DIAGRAM OF THE PROPOSED OPERATIONS INVOLVED IN THE CONCEPTUAL DESIGN OF AN ACTIVE DECONTAMINATION FACILITY

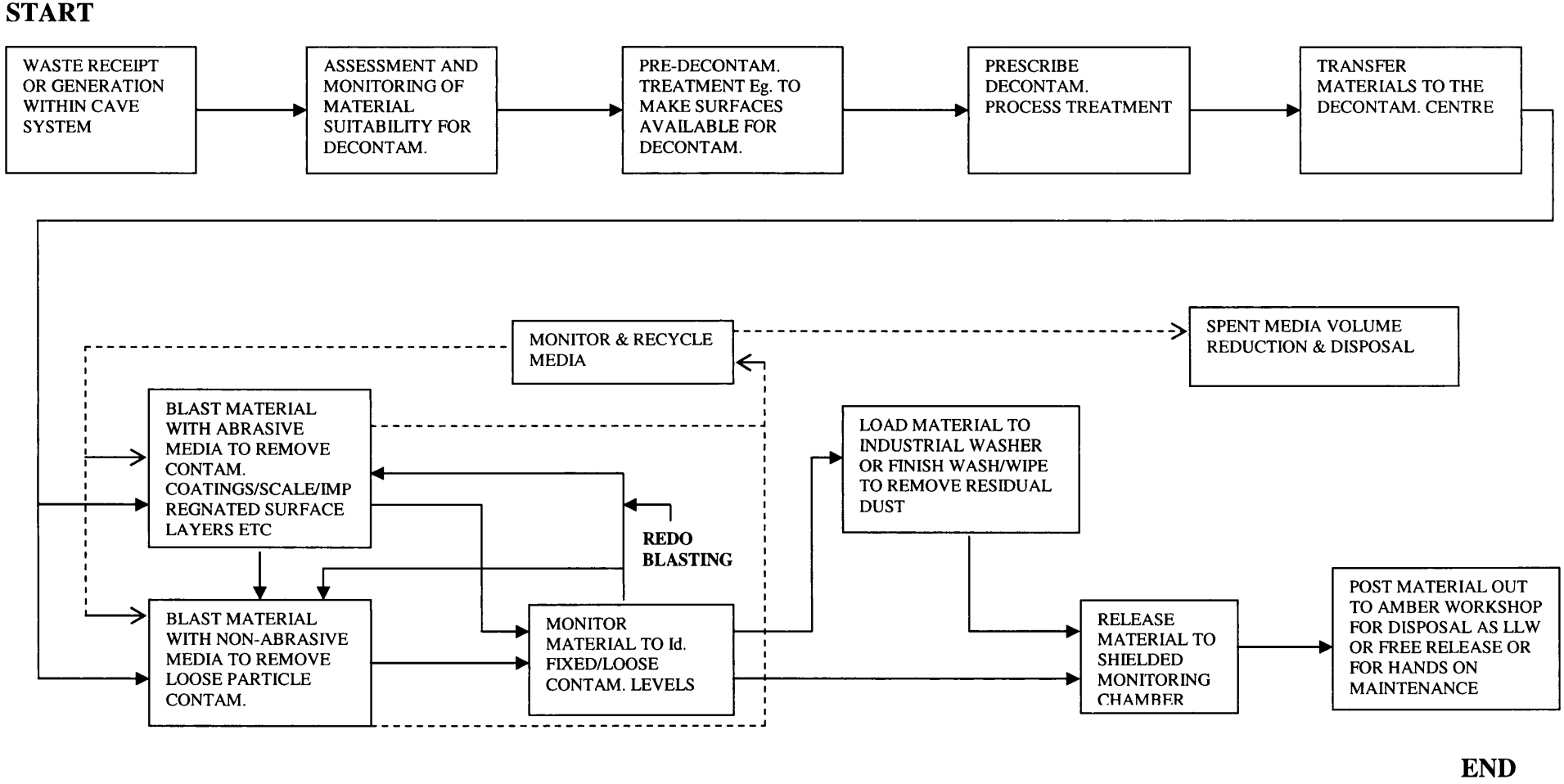
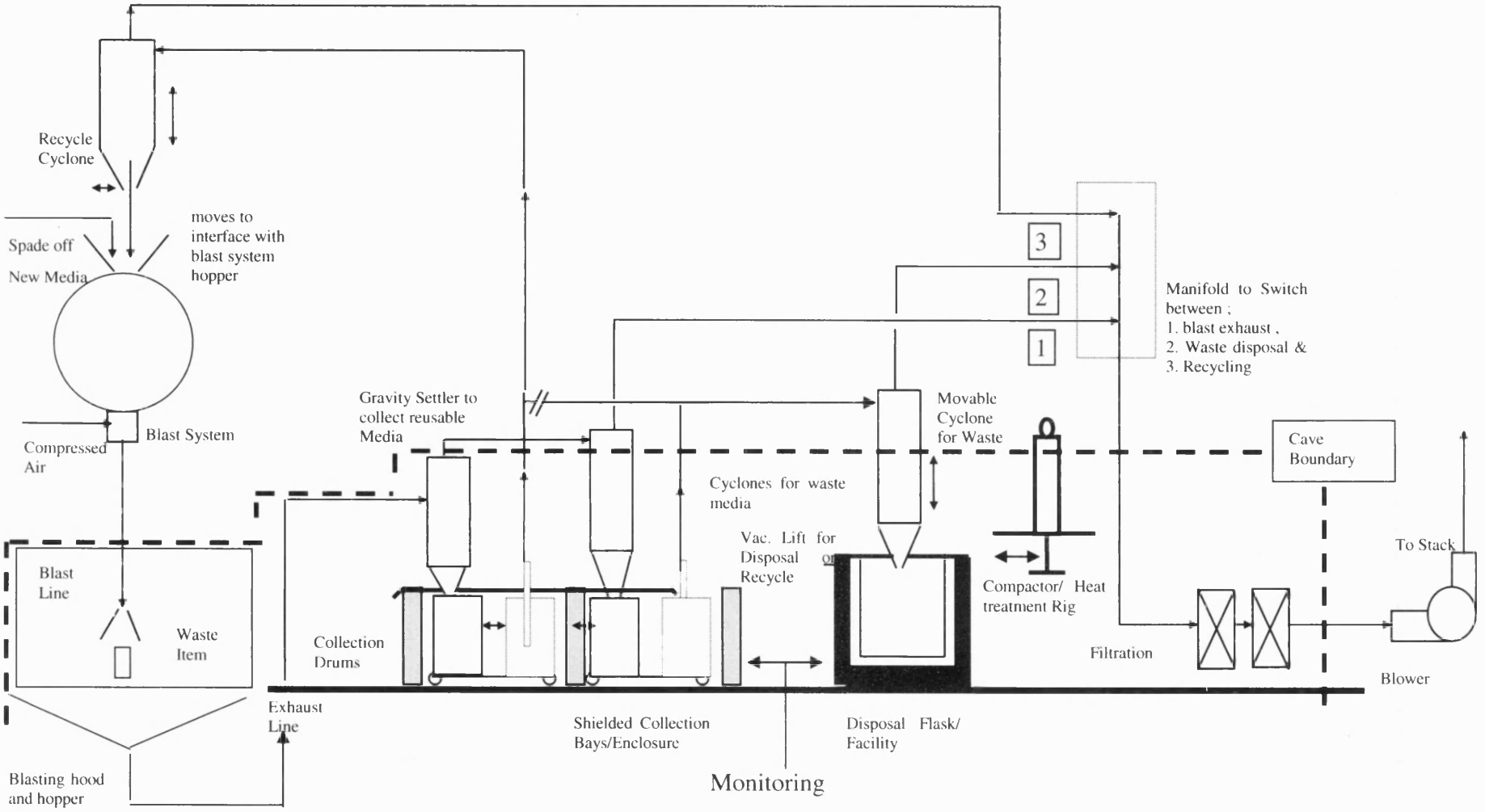


FIGURE 3.3b: PROPOSED CONCEPTUAL SYSTEM DESIGN FOR A DRY DECONTAMINATION SYSTEM IN A WAHF CAVE



Gravity Settlers

Differential settling of particles within a fluid moving through a gravity settler depends on a number of parameters; the density difference between particle and fluid (ρ_1 - ρ_2), the force that gravity exerts (F_g) on the particle, frictional resistance (due to viscosity (μ) of the fluid, particle on particle/vessel impingement, buoyancy, drag coefficient (C_d), Reynolds number (N_{re}), velocity of the fluid (v), size or diameter of the particle (d), and size of the settler [79]. By using these parameters it is possible that a satisfactory design can be modelled for a fluid flow rate through the system. It is likely that drag on a settling particle in this concept will behave in a manner akin to upper 'Allen flow' where the Reynolds number is up to 500, or lower 'Newton flow' where the Reynolds number might be any where from 500 to 10^5. The particles have rough surfaces and are not solid or rigid, but they do have a relatively consistent bulk density. Their size or diameter (d) varies from <1-2 mm (spent waste medium) up to 10-15 mm (for as-new or reusable medium). Settling is the simplest form of separation process and it relies purely on gravitational force. Provided the particles have a greater density than the air in which they are travelling, gravity will give the particles a settling velocity that is proportional to their density, the square of the particle diameter and inversely proportional to the viscosity of the fluid.

$$V_s \propto \frac{\rho \, d^2}{\mu_f} \qquad \text{.....(3.3.1)}$$

Where ρ is the particle density (kg m^{-3}), d is the particle diameter (m) and μ_f is the fluid viscosity (kg $m^{-1}s$). Specifically the settling velocity (V_s) under gravity is given by;

$$Vs = \frac{d^2}{K}\frac{(\Delta_1 - \Delta_2)}{\mu_f}.g \qquad \text{.....(3.3.2)}$$

where $(\rho_1 - \rho_2)$ is the difference in densities, and K is a constant derived from the drag coefficient that is itself a function of the Reynolds number $dV_f\rho_1/\mu$ (where μ is viscosity of the fluid).

Cyclone Separators

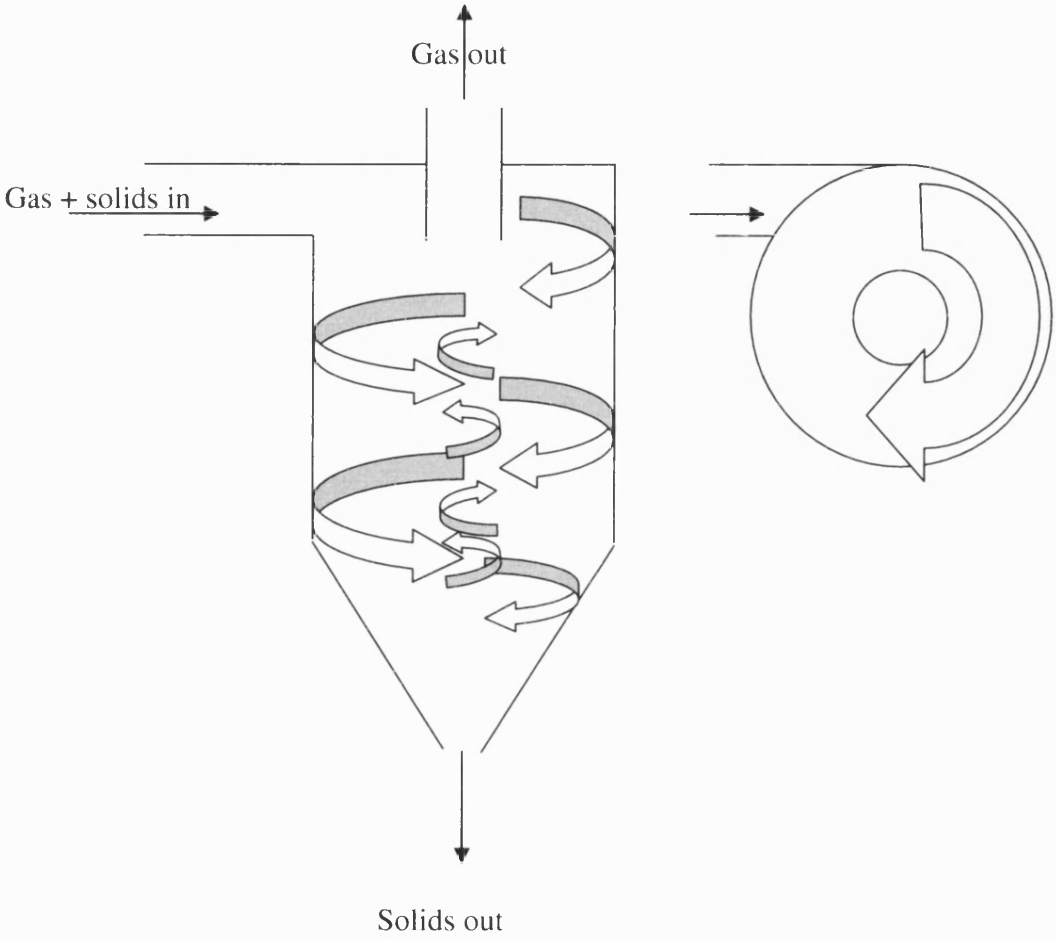
A conventional cyclone separator is a very effective piece of equipment for the removal of particles above 10 μm. Some high efficiency cyclones are able to remove some PM-10 (<10 μm) particles effectively. The equipment is usually a vessel in the form of a vertical cylinder arranged in such a way that air laden with particulate is directed around the vessel in spirals. This creates centrifugal forces that act on the particles throwing them onto the walls of the vessel. Usually the air will enter the cylinder tangentially where it will spin in a vortex as it proceeds down the cylinder. A cone section at the bottom causes the vortex diameter to decrease until the gas reverses on itself and then spins up the centre of the cylinder to the outlet pipe at the top of the cylinder. The forces throwing the particles to the wall cause inertial impingement, slowing them down in the gas boundary layer where they are discharged at the end of the cone section. This is a tangential inlet-axial discharge type of separator (see Figure 3.3c), that is reasonably economic in terms of space requirements, and are usually between 600 mm and 900 mm in diameter, although they can be smaller and larger depending on the purpose to which they are being applied. Other types include the tangential inlet-peripheral discharge cyclone where the cone is replaced by a peripheral purge air-flow to remove the dust saving space. Also there are the axial inlet-axial discharge and axial inlet-peripheral discharge cyclones where the air-flows stay in the same plane, reversing direction in the

former and not changing in the latter. These latter types are useful where changes of gas direction would be inconvenient, but they involve mechanical moving parts (to generate the centrifugal forces in the air stream) which will require a greater degree of maintenance than the tangential types [79 - 83].

The selection of the cyclone type and size depends on the collection efficiency or performance required of the equipment, although there are other factors which can impair the performance of the cyclone such as mechanical defects and the ability for them to be readily repaired can also influence selection. Clogging and excessive wear may also influence maintenance intervention. Assuming the cyclone has been sized correctly mechanical defects or problems that will involve intervention will be minimal with the conventional tangential inlet – axial discharge cyclone. There are no moving parts. This has significant advantages for its application at the WAHF, where any intervention will involve operator radiation dose uptake. Given the nature of the sponge medium it is to be expected that erosion will occur in the separation plant. This can be accommodated in the final design of such plant if this work is successful and the process is adopted for in-cave use at the WAHF, by appropriate selection of abrasion resistant materials and life cycle design thickness. When sizing such a cyclone the key parameters that need to be considered are collection efficiency and pressure drop. The cross-sectional area and length of the cyclone influence these parameters. The diameter of the cyclone influences the collection efficiency, where smaller diameters between 200mm and 600mm provide higher efficiencies. The ratio between the discharge port and the cyclone diameter (D) is usually between 0.18 and 0.40, with the higher ratios being found on large diameter cyclones intended for trapping coarser particles. The height of the cyclone will also affect flow resistance and collection efficiency, where increasing height increases resistance and efficiencies. Heights of cyclones overall can vary from 2D to 6D [82]. Cone apex angles

usually lies between 10 and 20 degrees, with the smaller angles being applied to the high efficiency units.

FIGURE 3.3c: CONVENTIONAL CYCLONE ARRANGEMENT



The centrifugal forces that a cyclone applies can range from a few times gravity in low velocity systems to several thousand times gravity in higher velocity systems. The smaller particles (down to ~5 μm) involved with high efficiency cyclones means that usually Stoke' Law can be considered to be valid. It can be assumed that the particles quickly reach their settling velocities, or for centrifugal motion, radial settling velocity (V_{sR}), and gives rise to the equation;

$$Vsr = \frac{\omega^2 r}{18} \frac{d^2}{\mu} (\rho_1 - \rho_2) \qquad \text{.....(3.3.3)}$$

where $\omega^2 r$ is the acceleration due to a centrifugal force (m s^{-1}), r is the radial distance from the centre of rotation (m) and ω is angular velocity (rad s^{-1}).

The higher the settling velocity the larger the radial velocity, therefore the easier it should be to 'settle' the particle. It is difficult to evaluate the radial velocity, since it is a function of the gravitational settling velocity, tangential velocity and the position of the particle both radially and axially in the cyclone. It is therefore easier to use an empirical equation;

$$Vsr = \frac{b_1}{18} \frac{d^2}{\mu} \frac{(\rho_1 - \rho_2)}{r^n} \qquad \text{.....(3.3.4)}$$

where b_1 and n are empirical constants.

Smaller particles might not reach the wall of the cyclone in order to be collected due to their smaller settling velocities, and may be retained in the exit air-flow. Larger particles will be easily collected. The efficiency of separation for a given particle diameter is the mass fraction of that size of particles collected. For a particular cyclone design the efficiency will rise dramatically across a certain particle size range. The challenge for this design problem will be to get this range as low as possible to ensure the cyclone traps as efficiently as it can at the lowest particle diameter possible in order to protect the filters from unnecessary loading and diminished life span. This particle size is known as the cut

diameter (D_{pc}), the particle diameter at which one half of the mass of entering particles is retained.

Since the shapes of the reusable particles are highly irregular, part of the initial trials will undertake to characterise the key dimensions and weights of these particles, and differentiate them from the waste or spent particles. This should provide a definition of the reusable to non-reusable partition size that the differential settler and cyclone should be designed to achieve.

Table 3.3a summarises the equipment to be used. The equipment will then be set up in the inactive mock-up facility to undertake non-radioactive proving trials. It would be possible to utilise the cave ventilation (blower and filters) to simulate the flow trials and achieve the designed flow rates through the system. A flask receipt well could be adapted to house the blast hood hopper. Figure 3.3d describes the design layout agreed for manufacture and build of the test rig at the Mock-up facility. Figure 3.3e shows the rig as built just prior to trials starting.

Following successful trials in the cave mock-up facility it is planned to adapt the LLW trial facility to undertake actual higher activity trials. The same prototype equipment will be set up in the enclosure, but the ventilation will change from the original 'passive' cave system line, to a forced ventilation that delivers the designed flow rates through the separators. The enclosure will effectively act as cave containment. More heavily contaminated pieces of waste will be identified for the trials.

TABLE 3.3a: DETAILS OF EQUIPMENT AND MATERIALS USED IN THE HIGHER ACTIVITY TRIALS

Equipment / Materials	Description
Spongejet Blasting System	240 Litre Feed Unit
Compressor	After cooled capable of delivering $6m^3$ of oil-free air at 0.7MPa
Silver sponge medium	Polyurethane foam particles containing abrasive aluminium oxide grit (bulk density ~$535Kg.m^{-3}$)
Green sponge medium	Polyurethane foam particles only
Personal Protective Equipment (PPE inc Radiological PPE)	Integral dust mask and visor, gloves, ear defenders, overalls and protective apron, full PVC suite, radiological monitoring and dosimetry equipment
Collection and Sampling Equipment Hot Wire Anemonitor (flow checking and calibration of blower control)	Dust pan and brush, collection bags, sample containers
Blast Hood with viewing windows and nozze supports that are MSM friendly (including cranage links)	Mild steel sheet (welded) – 1 m^3 overall, 0.3 m^2 window
Hood Support with hopper, including support frame for rotary table and motor.	Mild steel sheet (welded) – 1 m^2 reducing to 0.1 m^2
Gravity Settler + collection bin	Mild steel sheet (welded) – to be modelled
Cyclone + collection bin	Mild steel sheet (welded) – to be modelled
Flexible ducting to connect system components	Say 100 to 150mm diameter and approx. 10 m long
Cave Mock-up Facility (for inactive trials on the higher activity trial prototype system)	Exact copy of Cave 1 at the WAHF, including a filter bank and blower with the capacity to achieve the cave extract requirements (sufficient for blasting trials)
Steel vessel (waste item replica) Paint (to replicate contaminated surface coatings)	Stainless Steel - ~250 mm dia. by ~600 mm high.
Blast containment and extraction system (for use in the higher activity trials)	Modular shed of inside dimensions 4.0m(L) x 3.25m(W) x 2.4m(H) with side windows for external supervision, roof access for crane(loading waste or equipment), and barrier access for man entry. Extract lines to the Cave system, services for lighting, blasting lines, control lines and airborne monitoring.
Air sampler	This is used to extract air from the shed during the trial and collect active particulate
Blower/ filtration	Two filters in parallel see Fig 3.3g
Press Die (four off)	Ex-fuel decanning equipment
Die Blocks (two off)	Ex-fuel decanning equipment
SEM sticky Stubbs	Filter sampling

FIGURE 3.3d: CONCEPTUAL DESIGN LAYOUT FOR PROTOTYPE HIGHER ACTIVE TRIAL RIG

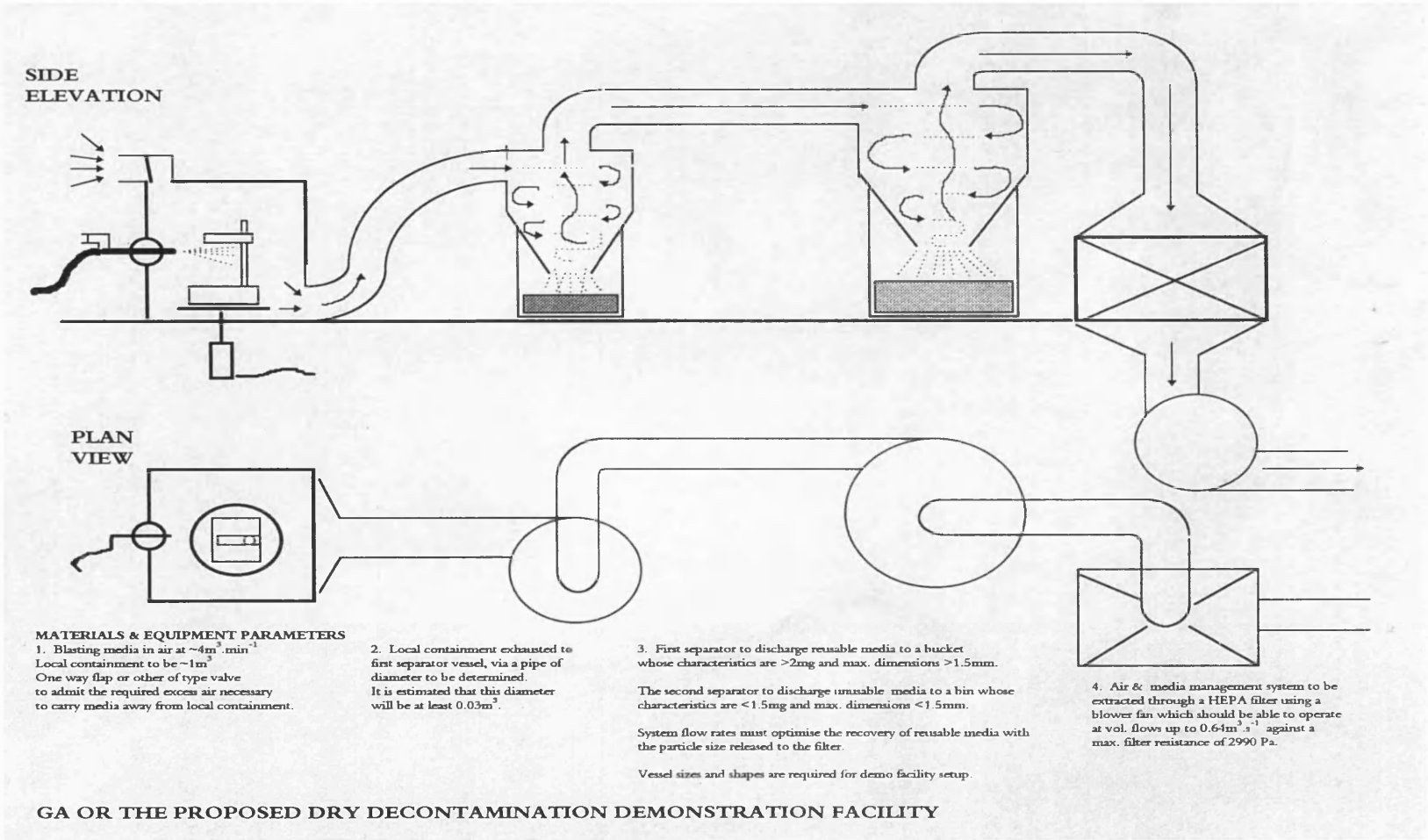


FIGURE 3.3e: THE PROTOTYPE HIGHER ACTIVE TRIAL TEST RIG AS SET UP READY FOR COMMISSIONING TRIALS

View of the mock-up system with the blast booth on top of hopper (furthest), with hose leading to the gravity settler (middle), leading on to the cyclone (near), the hose finally runs off screen (right) to the filters, fan then out of the building.

PU Volume Reduction

The sponge medium will need to be volume reduced when it is spent in order to minimise waste volumes for disposal and storage. The medium is dry and light enough to be 'hoovered' from one place to another in a contained manner. The sponge will compact under applied pressure with considerable gains in volume reduction. Compaction facilities are already available in the WAHF that could be used to process this material for disposal, but the medium will expel considerable amounts of air. Since one of the advantages of the Sponge-jet decontamination process is that the sponge retains

contaminants, it would be self-defeating to push much of that material out and around the cave. There is also a super-compaction facility at BNFL, Sellafield, which could mean the sponge might be disposed of directly with out volume reduction, but this may incur financial penalties.

A prototype heat treatment rig will be developed to test whether sponge medium can be volume reduced using a form of compression moulding, where the pores of the sponge particles are closed under heat and pressure to weld them shut, thus encapsulating the contaminants in-situ. This will hopefully make the medium cleaner to handle (remotely), more manageable and enable the benefits of volume reduction to be realised.

3.3.2 Higher Active Trial Objectives

The aims of this phase of work can be separated in to 1) inactive development studies and then 2) radioactive trials. These stages of the project can then be further broken down as follows;

1. Design and develop a prototype decontamination system suitable for demonstrating its deployment in a cave at the WAHF;
    - install equipment in the inactive cave mock-up facility,
    - prove its operating capability and the recycle-ability of medium processed through the system,
    - define the recycle parameters for the system,
2. Adapt prototype decontamination system for higher activity trials using the LLW trial enclosure;
    - install the prototype decontamination system in the

LLW and prove its operability,

- undertake higher activity trials on suitably selected waste items to collate data on decontamination performance, medium management system performance in terms of both medium recycling and contamination transfer to each stage of the system.

In conjunction with this work on the decontamination process a parallel area of study will be carried out in scaling up heat treatment of sponge medium in order to look at the feasibility of using compression moulding as a means of volume reduction[58, 84].

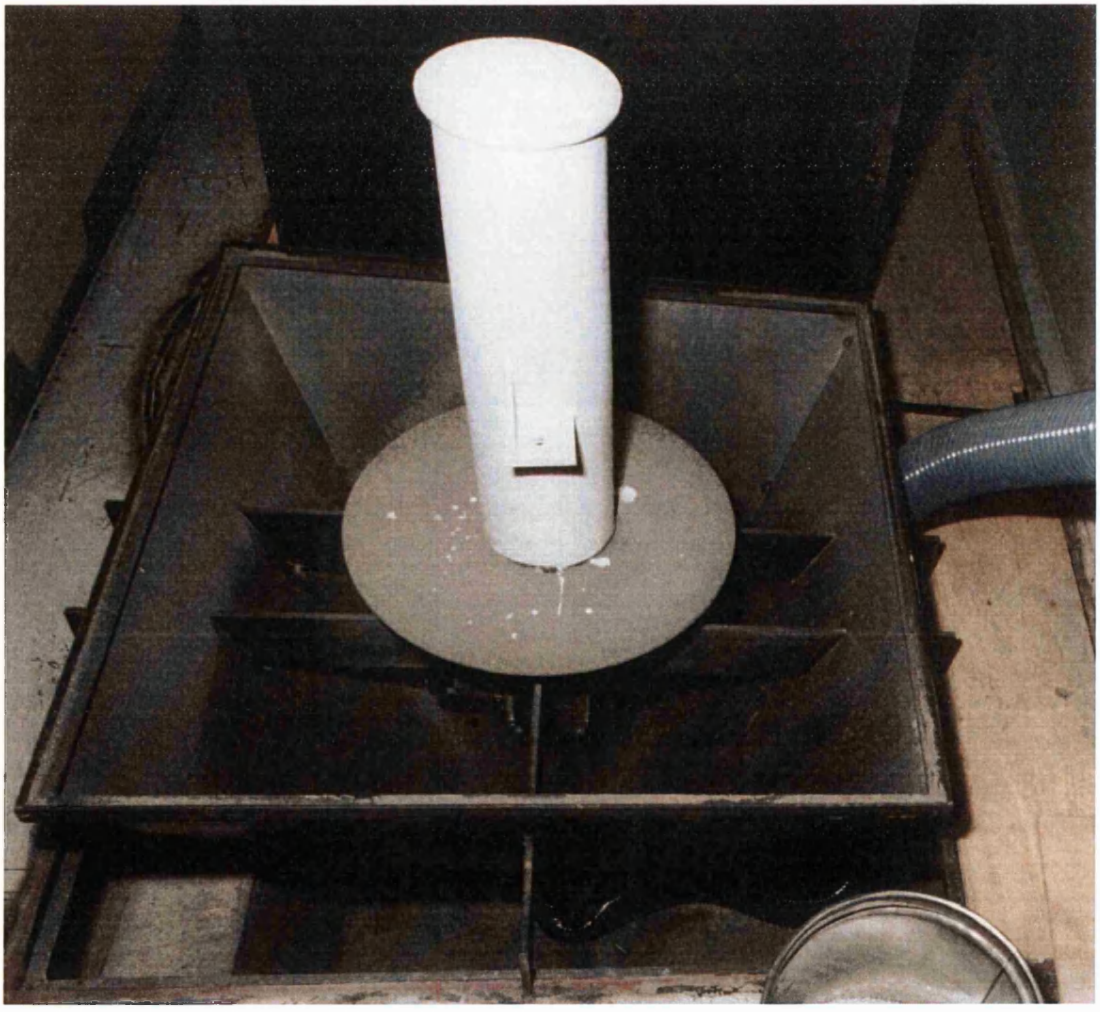
3.3.3 Higher Active Trial Design

Once the prototype system has been developed and installed in the inactive cave mock-up facility the blower fan control will be calibrated for achieving the design flow rates. The specimen to be used in the blasting trials consisted of a stainless steel vessel that had been welded onto a rotary turntable. This vessel is typical of the waste that the WAHF will be disposing from decommissioning projects over the forthcoming years. The vessel would be painted with an epoxy paint to simulate a moderately tenacious contamination coating. The silver abrasive medium would again be used. The settler and cyclone collection bins were 15 litre paint tins so the blasting and recycling trial would be limited to one charge of this volume. Figure 3.3e shows the system as set up in the mock-up facility and Figure 3.3f shows the steel vessel and turntable arrangement. The blast nozzle is mounted on a fixed MSM friendly tilt and pan station in the side of the blast hood, which combined

with the rotation of the turntable allows the sponge medium to be blasted at all areas of the vessel.

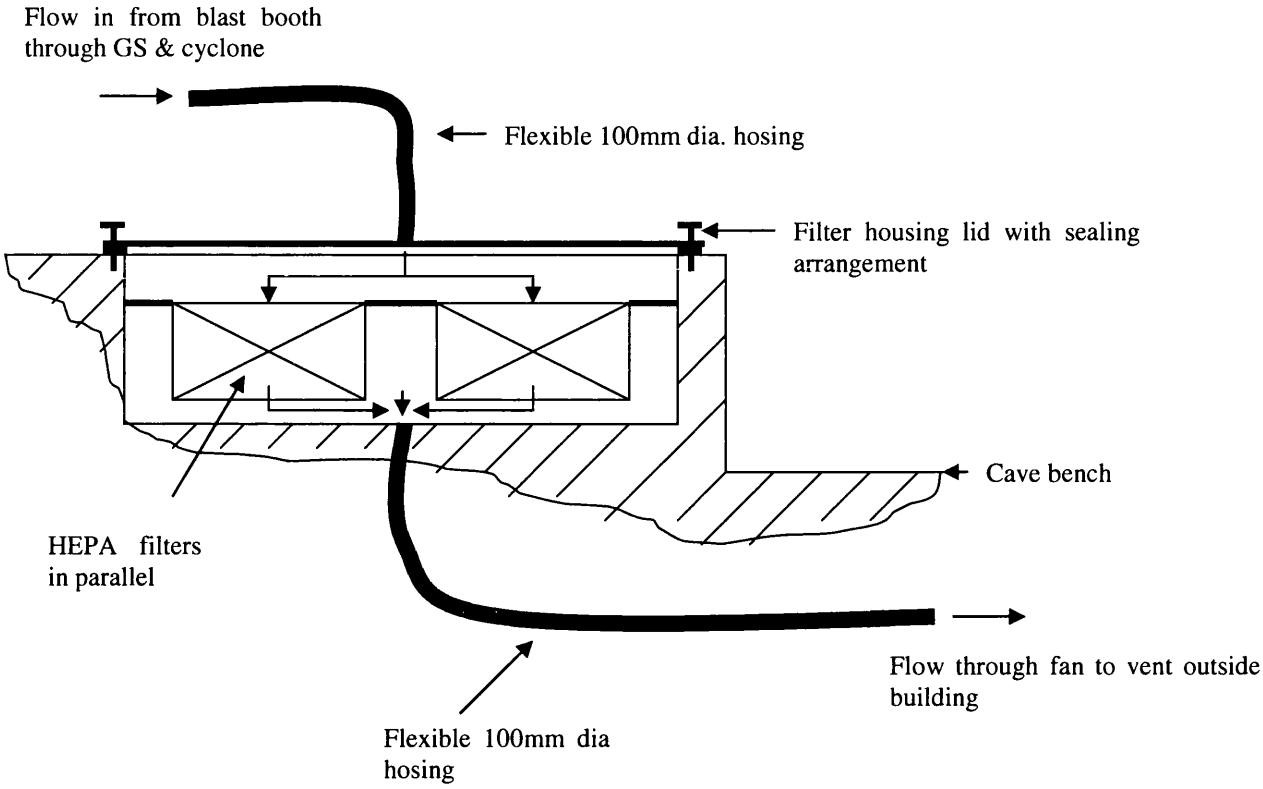
Figure 3.3g shows the HEPA filtration arrangement at the mock-up facility. Any debris in this area after the trials will provide some indication of how well the cyclone is working. Medium losses will be measured and samples taken at each stage for assessment of particle breakdown with each cycle. The effects of varying the flow rates will be assessed and the effect of lower blasting pressure.

FIGURE 3.3f: STEEL VESSEL (SIMULATING A WASTE ITEM) AND ROTARY TABLE ARRANGEMENT WITHIN HOPPER



Specimen on rotary table within blast booth above hopper.

FIGURE 3.3g: MOCK-UP FACILITY HEPA FILTER BANK ARRANGEMENT



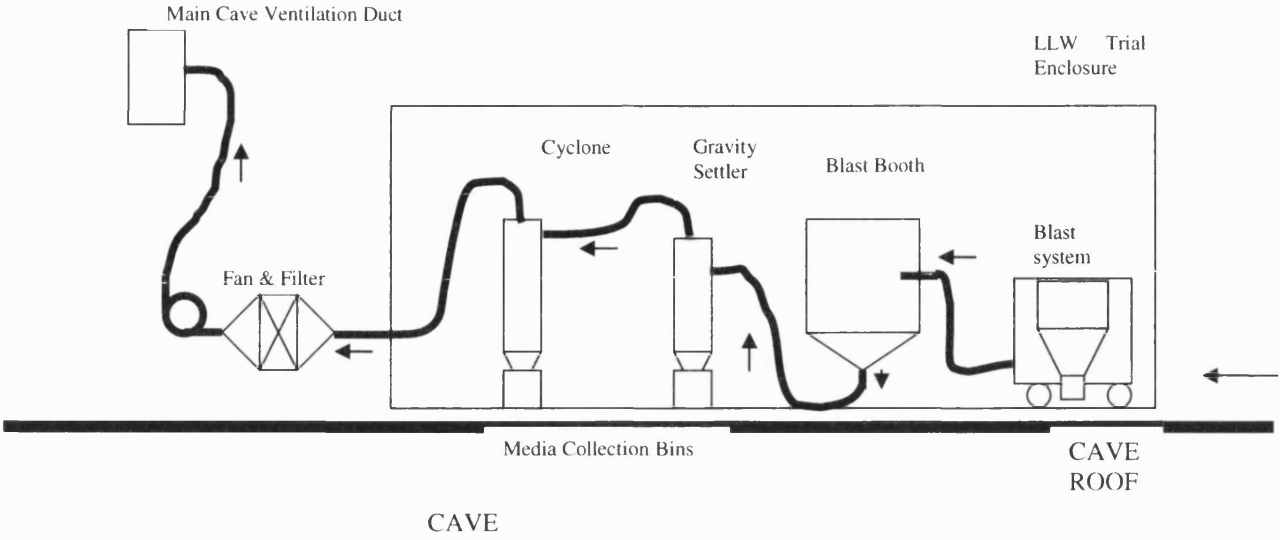
The work activities involved with the mock-up system trials can be summarised in two areas, firstly system commissioning and secondly the trials themselves. Commissioning initially required the system control to be set up by calibrating the facility ventilation blower control and measuring the mean duct flow rates through the separation system ducting. Specific identification of the 17-18 m s^{-1} control point is required to ensure the modelled 8 m^3 min^{-1} volumetric flow rate is achievable and can be maintained. Using a 'hot wire' anemometer the duct flows were measured at progressively higher fan speeds, and the controller calibrated accordingly. The system flow rates were then measured with the blast system running to test whether this would affect the duct flow rates and require adjustment of the fan speed to compensate. These tests should identify the flow rates at blast pressures ranging from 20 psi to 70 psi for the standard regulator settings on the Sponge-jet system. Any potential variant conditions should be noted during the trials and

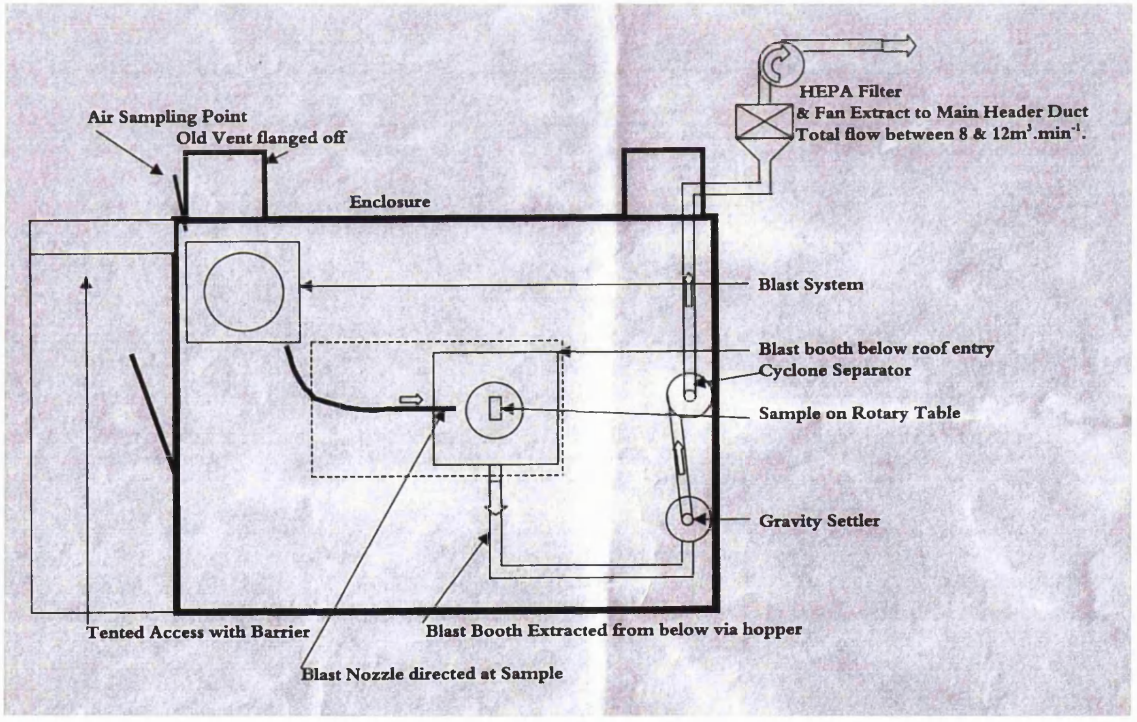
investigated. The two sets of tests should now permit adjustments of the system to compensate for different blasting and fan speed conditions should the separation system fail to work effectively at the modelled flow rates.

The system trials were to be carried out blasting Silver medium at the prescribed maximum blast pressures (70 psi) and blower extract (17-18 m s^{-1}). The system trial was conducted on a standardised basis by removing paint from the work-piece using one 15 litre paint tin load Silver medium. Blasting of the paint tin charge would be completed by an examination of the settler and cyclone collection tins to assess the effectiveness of the separation system. Checks would also be made on the filters for any medium carry over. The trials would be redone at lower or higher blower flow rates and the results recorded. After the completion of each blast stage samples would be taken of both the spent and the reusable medium, for further examination. Blasting could continue by recycling until the medium is all spent or it is no longer effectively removing the paint. A new paint tin charge of Silver medium would be used to test the system in the same manner as before to observe the effects of lower and higher flow rates.

The higher radioactivity trials will effectively involve the system set-up from the mock-up facility being replicated in the LLW trial enclosure. The LLW trial ventilation ducting to cave will be disconnected and a dedicated stand-alone blower and HEPA filter unit will then be connected to the enclosure via the cyclone. The discharge will be sent to the main cave ventilation system. Figure 3.3h describes this arrangement.

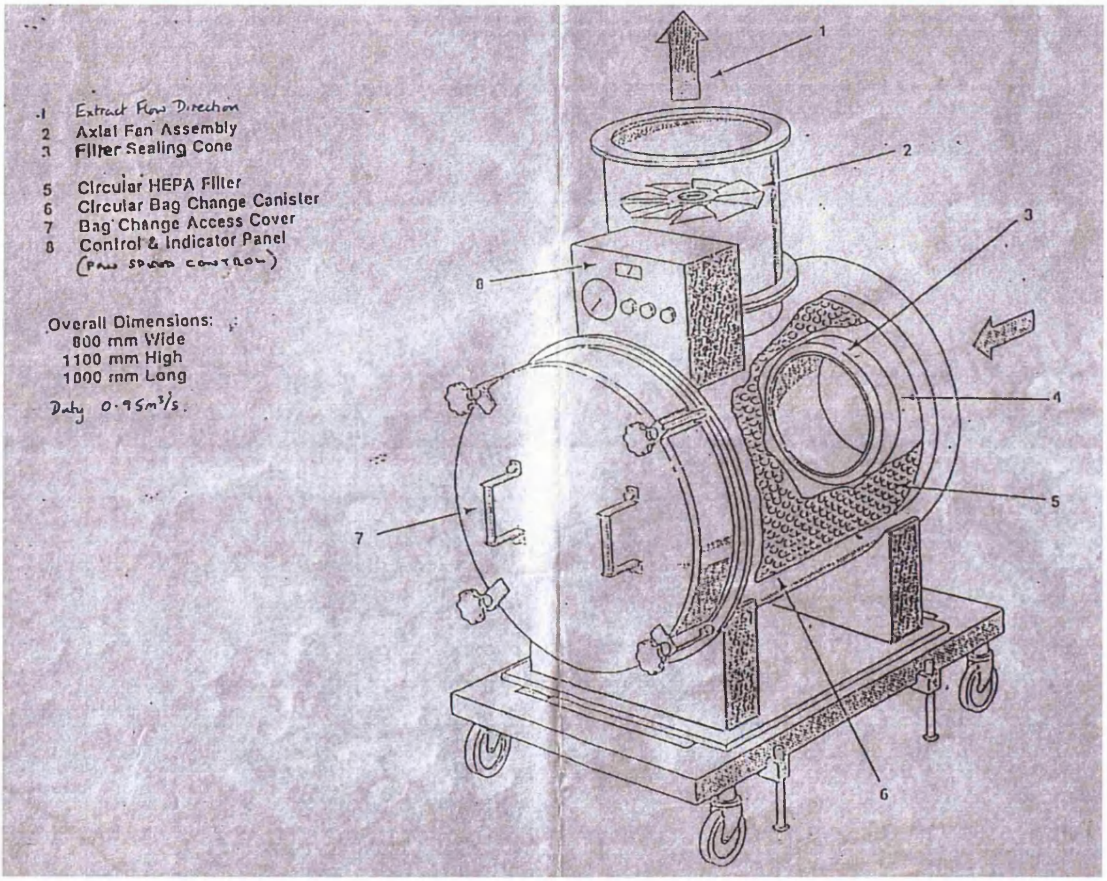
FIGURE 3.3h: HIGHER ACTIVITY TRIALS USING THE LLW TRIAL ENCLOSURE





Trials using the system before it goes active will confirm that it can achieve the flow rates that were proven in the non-radioactive trials at the cave mock-up facility. Figure 3.3i provides more detail of the mobile fan and filtration unit used for the trial.

FIGURE 3.3i: MOBILE FAN AND HEPA FILTRATION UNIT FOR HIGHER ACTIVITY TRIAL



A number of waste items were retrieved from an in-cave press rig used to de-clad uranium fuel. These consisted of two die blocks, four die and four tools. These items came into intimate contact with fuel elements and are contaminated with radioactive particles from both the fuel and the other waste in the cave. The contamination on these items is considered to be representative of wastes that generally arise from WAHF

operations. A standard fingerprint relates dose rates to surface contamination levels, which allows the radioactivity inventory of each waste item to be assessed prior to being decontaminated. Monitoring before and after the decontamination process will indicate how much radioactivity has been removed. Figure 3.3j shows the results of monitoring surveys made on these items.

FIGURE 3.3j: MONITORING SURVEY REPORTS FOR HIGHER ACTIVITY TRIAL SPECIMENS (Continued over)

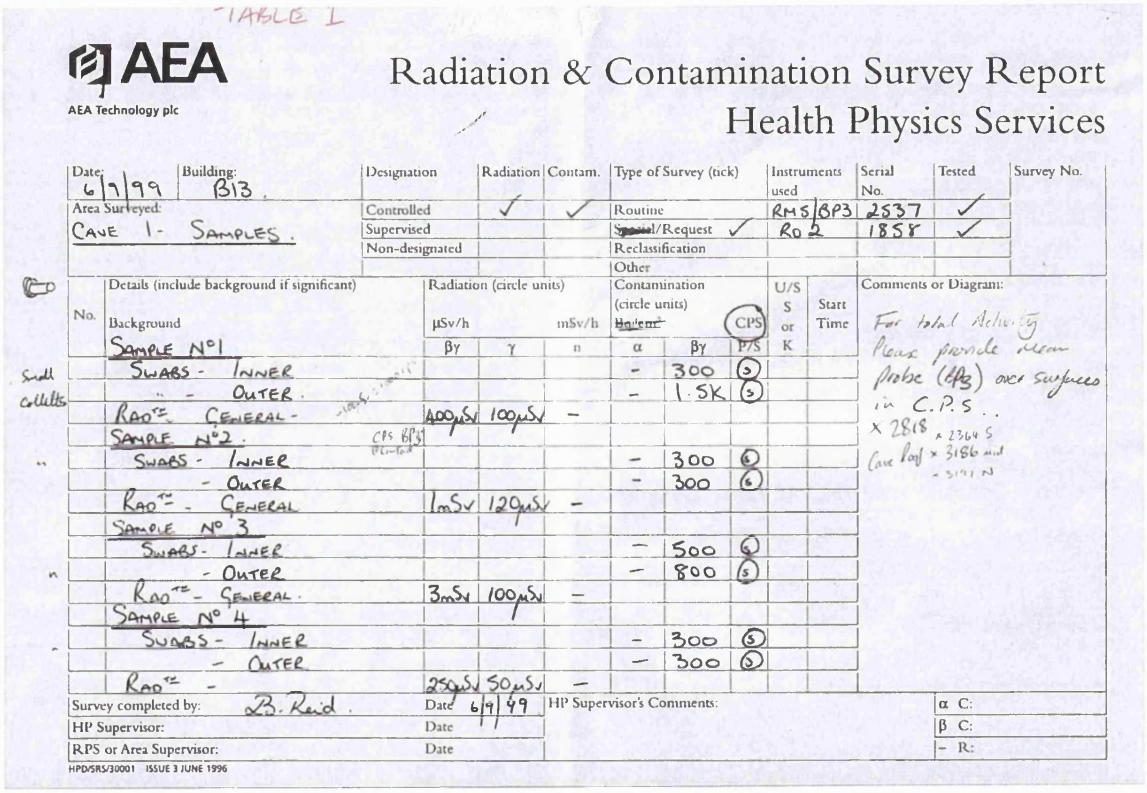


TABLE 1

AEA Technology plc

Radiation & Contamination Survey Report
Health Physics Services

Date: 6/7/99	Building: B13.	Designation	Radiation	Contam.	Type of Survey (tick)	Instruments used	Serial No.	Tested	Survey No.
Area Surveyed: CAVE 1 - SAMPLES.		Controlled	✓	✓	Routine	RMS/BP3	2537	✓	
		Supervised			Special/Request ✓	RO 2	1858	✓	
		Non-designated			Reclassification				
					Other				

No.	Details (include background if significant) Background	Radiation (circle units) µSv/h βγ	µSv/h γ	mSv/h n	Contamination (circle units) Bq/cm² α	Bq/cm² βγ	CPS β/S	U/S S or K	Start Time	Comments or Diagram:
	SAMPLE N°1									For total Activity Please provide mean Probe (BP3) over surfaces in C.P.S.
Small cobalts	SWABS - INNER				-	300	(5)			
	" - OUTER				-	1.5K	(5)			
	RAD^n - GENERAL -	400µSv	100µSv	-						
	SAMPLE N°2 (CPS BP3 Plastic)									
"	SWABS - INNER				-	300	(6)			
	- OUTER				-	300	(6)			
	RAD^n - GENERAL	1mSv	120µSv	-						
	SAMPLE N° 3									
	SWABS - INNER				-	500	(5)			
"	- OUTER				-	800	(5)			
	RAD^n - GENERAL.	3mSv	100µSv	-						
	SAMPLE N° 4									
	SWABS - INNER				-	300	(5)			
	- OUTER				-	300	(5)			
	RAD^n -	250µSv	50µSv	-						

Survey completed by: B. Reid.	Date 6/9/99	HP Supervisor's Comments:	α C:
HP Supervisor:	Date		β C:
RPS or Area Supervisor:	Date		- R:

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FIGURE 3.3j Continued

TABLE 2

AEA Technology plc

Radiation & Contamination Survey Report
Health Physics Services

Date: 6/9/99	Building: B13	Designation	Radiation	Contam.	Type of Survey (tick)	Instruments used	Serial No.	Tested	Survey No.
Area Surveyed: CAVE 1 - SAMPLES CONT'D		Controlled	✓	✓	Routine	RMS BP3	2537	✓	
		Supervised			Special/Request ✓	RO2	1858	✓	
		Non-designated			Reclassification				
					Other				

No.	Details (include background if significant) Background	Radiation (circle units) µSv/h βγ	γ	mSv/h n	Contamination (circle units) Bq/cm² α	βγ	CPS P/S	U/S S or K	Start Time	Comments or Diagram:
	SAMPLE N° 5.									
	SWABS - INNER				-	200	(S)			
	OUTER				-	200	(S)			
	RAD'N -	800µSv	150µSv	-						
	SAMPLE N° 6.									
	SWABS - INNER				-	1·5K	(S)			
	OUTER				-	1·5K	(S)			
	RAD'N - BROAD END	3mSv	100µSv	-						
	- NARROW END.	1·5mSv	100µSv	-						
	SAMPLE N° 7									
	SWABS - INNER				-	1K	(S)			
	- OUTER.				-	500	(S)			
	RAD'N - BROAD END	250µSv	100µSv	-						
	- NARROW END	2·5mSv	100µSv	-						

Survey completed by: B. Reid	Date 6/9/99	HP Supervisor's Comments:	α C:
HP Supervisor:	Date		β C:
RPS or Area Supervisor:	Date		- R:

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TABLE 3

AEA Technology plc

Radiation & Contamination Survey Report
Health Physics Services

Date: 6/9/99	Building: B13.	Designation	Radiation	Contam.	Type of Survey (tick)	Instruments used	Serial No.	Tested	Survey No.
Area Surveyed: CAVE 1 - SAMPLES CONT'D		Controlled	✓	✓	Routine	RMS BP3	2537	✓	
		Supervised			Special/Request ✓	RO2	1858	✓	
		Non-designated			Reclassification				
					Other				

No.	Details (include background if significant) Background	Radiation (circle units) µSv/h βγ	γ	mSv/h n	Contamination (circle units) Bq/cm² α	βγ	CPS P/S	U/S S or K	Start Time	Comments or Diagram:
	SAMPLE N° 8									
	SWABS - INNER				-	200	(S)			
	- OUTER				-	3K	(S)			
	RAD'N - GENERAL	2mSv	120µSv	-						
	SAMPLE N° 9.									
	SWABS -				-	200	(S)			
	RAD'N - GENERAL.	1mSv	150µSv	-						
	SAMPLE N° 10.									
	SWABS -				-	2K	(S)			
	RAD'N GENERAL.	3·5mSv	100µSv	-						

Survey completed by: B. Reid	Date 6/9/99	HP Supervisor's Comments:	α C:
HP Supervisor:	Date		β C:
RPS or Area Supervisor:	Date		- R:

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Sampling and monitoring of reusable medium and waste medium, swabbing of the hopper, gravity settler, cyclone and sampling at the filter will endeavour to track the transfer of radioactive contamination through the system. The methodology by which this will be achieved is as follows;

1. Ensure the extract and blast system is isolated. Fit SEM 'sticky stubs' across the filter' upstream face, ensure the collector bins are fitted and all hoses are connected. Carry out flow speed checks in the collector ducting (as per the mock-up commissioning) to confirm that the volumetric flow rates are between 8 $m^3 min^{-1}$ and 12 $m^3 min^{-1}$ (i.e. this should correlate with flow speeds of between 17 m s^{-1} and 25 m s^{-1}). (N.B. the corrugated (100 mm diameter) ducting and separators will give rise to turbulent flow, therefore flow speed measurements are necessarily best estimates across the duct diameter using a calibrated hot wire anemometer. Measurements should be at the entry and exit points to the separation system itself to ensure the earlier mock-up commissioning parameters are reproduced).

2. Clamp Sample No. 4 on to the rotary turntable and replace blast booth cover. Fit blast nozzle to blast booth.

3. Ensure the Sponge-jet blast system is isolated (i.e. the inlet valve, on-off switch and emergency stop are in the off position). Start compressor for the blast system. Load one collector bin (15 litres) of standard Silver medium to the blast system pressure vessel, and replace hopper cover.

4. Start the blast booth extract system and set to flow rates of 10 $m^3.min^{-1}$. Start rotary turntable and direct the blast nozzle, then switch on the blast system and decontaminate the sample. Blast the sample until all 15 litres of the medium has been used.

5. Switch off the blast system by releasing the deadmans handle, then isolate the blast system by pressing the emergency stop, turning the on-off switch to 'off', and the main line valve to 'off'. Switch off the extract system to the blast booth at least 30 seconds after the blast system has been shut down in order to clear all airborne materials from the ductwork.

6. Unclamp and remove the sample from the rotary turntable. Arrange for a full Health Physics (HP) survey using a BP3 probe (shielded), and by swab.

7. Carry out a HP survey by BP3 probe (shielded) and swab inside of the enclosure, working inward to the blast booth, hopper, gravity settler and cyclone. Collect data on the system containment during blasting.

8. Access the blast booth and hopper, the gravity settler bin and the cyclone bin. Take monitor using the BP3 probe and take swabs from system surfaces and samples of the reusable and spent medium, at the top and bottom of the collection bins.

9. Monitor fixed quantities of the medium samples in petri-dishes using the Scalar in the HP office.

10. Monitor all swabs in the Scalar.

11. Reinstate the system and enclosure containment, and switch off the extract fan, then isolate system from main building ductwork. Remove HEPA filter and remove SEM 'sticky stubs', then place in sealed bags for SEM analysis and assessment.

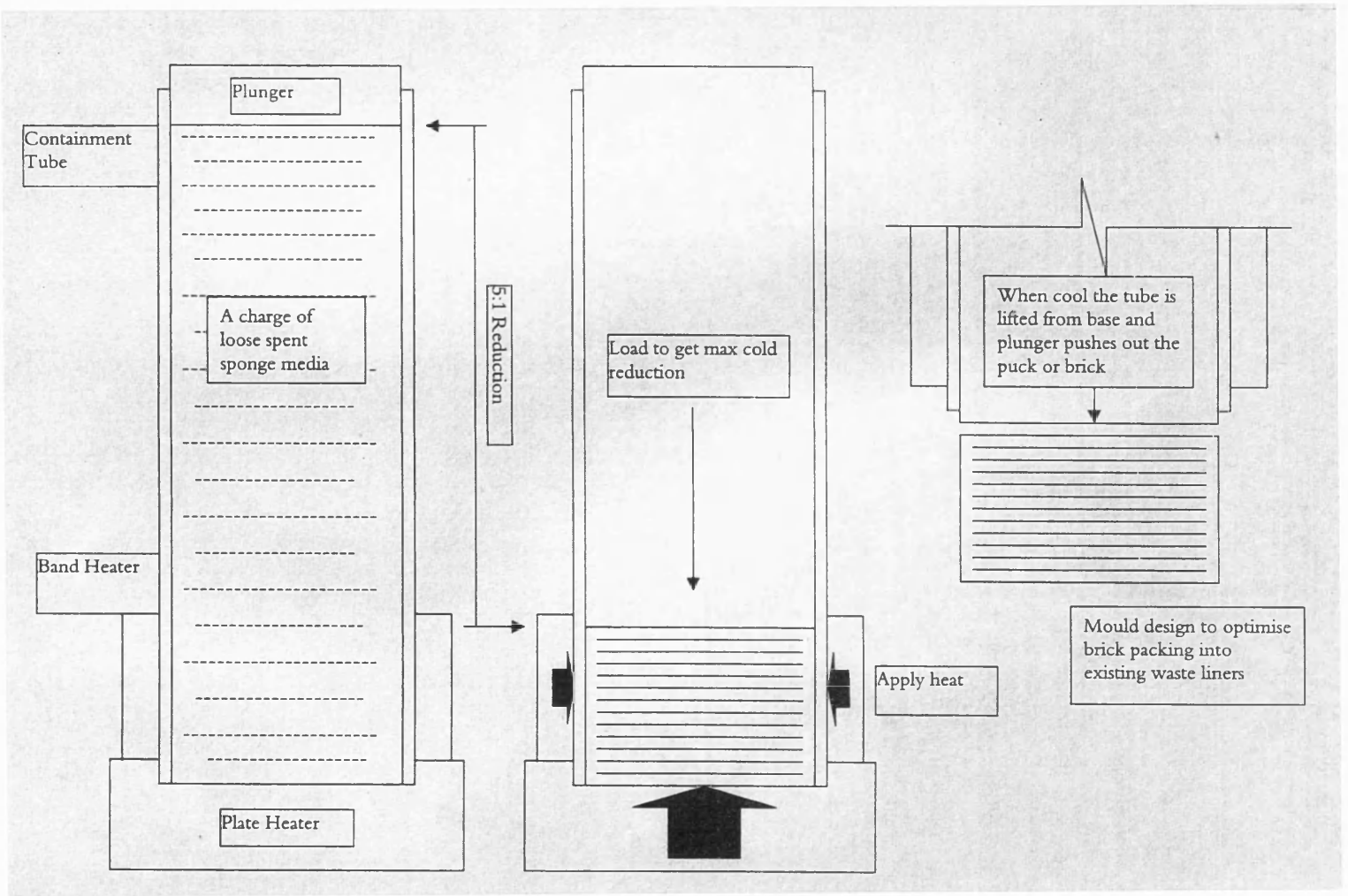
12. Reinstate filter and mobile extract system with new SEM 'sticky stubs', then reconnect to main building ductwork. Repeat the exercise for the next sample until all the specimens have been decontaminated.

This will provide information on which to assess the system's containment and contamination transfer characteristics, and model the overall performance of the process, to determine whether it is feasible to use the technology as an industrial decontamination process within the WAHF.

Volume Reduction

A simple conceptual design was developed to test the compression moulding approach to volume reducing the sponge medium. Figure 3.3k describes the arrangement of the design. Essentially the spent medium would be pneumatically delivered in sized batches to the mould chamber, which in this case is a length of tube. A plunger would compress the medium and then heat would be applied. These trials would test the feasibility of scaling up the trials conducted at the University of Bath [84]. The trials would initially be undertaken on spent medium from the inactive trials, but if successful and following an optimisation process, work would proceed to active trials. The active trials would firstly be done on medium from LLW trials, possibly in the enclosure.

FIGURE 3.3k: GENERAL ARRANGEMENT OF THE CONCEPTUAL DESIGN FOR THE DEVELOPMENT OF A TRIAL RIG FOR HIGHER ACTIVITY VOLUME REDUCTION STUDIES



3.4 SUMMARY

This chapter has provided a description of the experimental equipment and processes to be used in the initial Low Level Waste and higher activity trials, and it has discussed the aims of each set of trials, and the approach to how each area of study will be achieved in terms of the trial design. These areas have been presented in a step by step way from the initial non-radioactive work through progressively more radioactive studies. Clearly in 'real' time the subsequent trial designs were developed subject to the satisfactory outcomes from the previous trials.

CHAPTER 4 EXPERIMENTAL RESULTS AND DISCUSSION

4.0 INTRODUCTION

This chapter describes and reports the results of the trials carried out as described in Chapter 3. It covers the initial trial results, and the examinations conducted on samples taken during those trials. The LLW trials and the results of specific case studies are discussed, including specific investigations into the nature of the polyurethane media during recycling. Following both these stages volume reduction trial results are reported and discussed with a view to an integrated waste route. Finally the design and development of a higher activity trial test rig is described and discussed prior to the results of higher activity trials.

4.1 INITIAL NON-ACTIVE TRIAL RESULTS

4.1.1 Sponge Blasting

Table 3.1a shows the media material being studied, and Table 3.1d outlines the sampling and examination regime undertaken for the PU sponge media to be studied as a decontamination process. While non-abrasive media is unlikely to be effectively applied in any waste decontamination process, it could contribute to waste minimisation at the WAHF by cleaning tools for refurbishment and reuse. Samples of Green media were taken initially for comparative purposes with the abrasive media, which was studied in more detail, but an opportunity was taken to test the non-abrasive on a milling machine tool removed from the cave system for refurbishment (see Chapter 4.2). All blasting has been carried out at maximum blasting conditions (70 psi blast line pressure).

Table 4.1a summarises the results of inactive trials to assess the remote applicability of the sponge blasting process. Various metal plates were blasted (Figure 4.1a) at different

nozzle stand off and trajectories and samples then trepanned for examination. Measurements were taken of the plate thickness (using a standard micrometer), the changing impact width and surface roughness (using a rank Taylor Hobson Talysurf machine) with stand off and trajectory, respectively. The area of abrasion has a diameter that increases from ~25 mm at a 100 mm nozzle stand-off, to ~70 mm diameter at a 300mm nozzle stand-off. The feed rate was kept constant at ~50 mm per second (nozzle centre line across surface) for each traverse at each angle of nozzle trajectory and stand-off distance. The surface roughness measurements, as an indication of abrasion effect varied from 20-25 μm R_a for a 100 mm stand-off down to 10-15 μm R_a at stand-off's from 150 mm to 300 mm on the mild steel, with similar roughness being measured for stainless steel materials. Even after prolonged blasting in the same spot at 150 mm stand-off, the surface roughness remained consistent at 15.5 μm R_a (see Figure 4.1b). While R_a is the universally recognised and most used parameter to characterise surface roughness (i.e. the arithmetic average deviation from the mean line of the roughness profile, also known as the centre line average), other parameters have also been calculated automatically such as R_q (the root mean square roughness), R_p and R_v (maximum peak and valley deviation from the centre line) and R_t (the maximum distance between R_p and R_v). For the example given in Figure 4.1b R_q is 19.9 μm (corresponding to the R_a of 15.5 μm), R_p is 59.6 μm, R_v is 65.1 μm making the maximum peak to valley roughness height (R_t) 124.7 μm, for the sample length (L_o) of 6.2 mm. The softer aluminium plate revealed higher surface roughness at larger stand-off distances (Figure 4.1c). At shallower trajectories some directionality was observed. This tends to suggest that the process is relatively insensitive within the trial variations in these two parameters. Time trials blasting the same area of plate show that considerable depths of material can be removed depending on the feed rate of the process. Static trials demonstrated that the process was

TABLE 4.1a: INACTIVE SPONGE BLASTING TRIAL TARGET MATERIAL RESULTS SUMMARY

Media Type	Target Material	Stand-off Dist.(mm)	Impact zone width (mm)	Surface Roughness (Ra,μm) at Angle of Incidence*					Start Thickness (mm)**	Vickers Hardness (Hv)***	Abrasion – material thickness after set time intervals(secs)				
				90°	70°	50°	30°	New			10	20	30	60	120
Abrasive - Silv. PU media embedded with Al oxide grit	Mild Steel (43A)	100	25	21	19	12	13	2	6.05	154	6.07	5.97	5.79	4.98	3.94
		150	30	12	15	16	13	2							
		200	35	14	15	19	14	2							
		250	43	13	12	11	14	2							
		300	60-70	13	10	9	11	2							
	Stainless Steel (304)	150	30	11	15	14	17	6	6.15	229	-	5.92	-	-	3.25
		300	60-70	12	10	13	12	6							
	Aluminium (L54?)	150	30	18	17	20	19	<1	6.08	85	-	5.54	-	-	1.96
		300	60-70	20	25	19	19	<1							
Non-abrasive- Green PU only	Mild Steel (43A)	50-100	-	5	-	-	-	2	6.05	154	-	-	-	-	-
		150-200	-	3	-	-	-	2							

* The feed rate was kept constant at ~50 mm s^{-1} (~300 mm in 6 seconds) as far as possible, however this was a manually deployed trial with only guidance aids, other errors that might arise during the trials could be due to variability inherent in the process and media (e.g. medium/grit density/size), directionality of abrasion/cutting action trajectory, variability in the plate material structure and measurement errors. These errors have been minimised as far as possible by the trial design. Using rolled plate should ensure reasonable consistency of structure, and by following correct operating practice for the Talysurf machine. Investigating the variability in the process and sponge media is part of this study, but it is expected that the deployment (stand-off and trajectory) errors far outweigh any other areas of uncertainty in the trial, but these were also minimised as shown by measurement of blast impact path (repeatable within +/- 2 to 3 mm). Between 100 mm and 300 mm the blast zone suggests the angle of fire widens at a generally uniform rate with distance, only widening at an increased rate at as 300 mm stand-off.

** Mild steel thickness varied from 6.03 mm to 6.07 mm, stainless steel 6.12 to 6.17 mm, and aluminium 6.06 mm to 6.10 mm, as measured y micrometer.

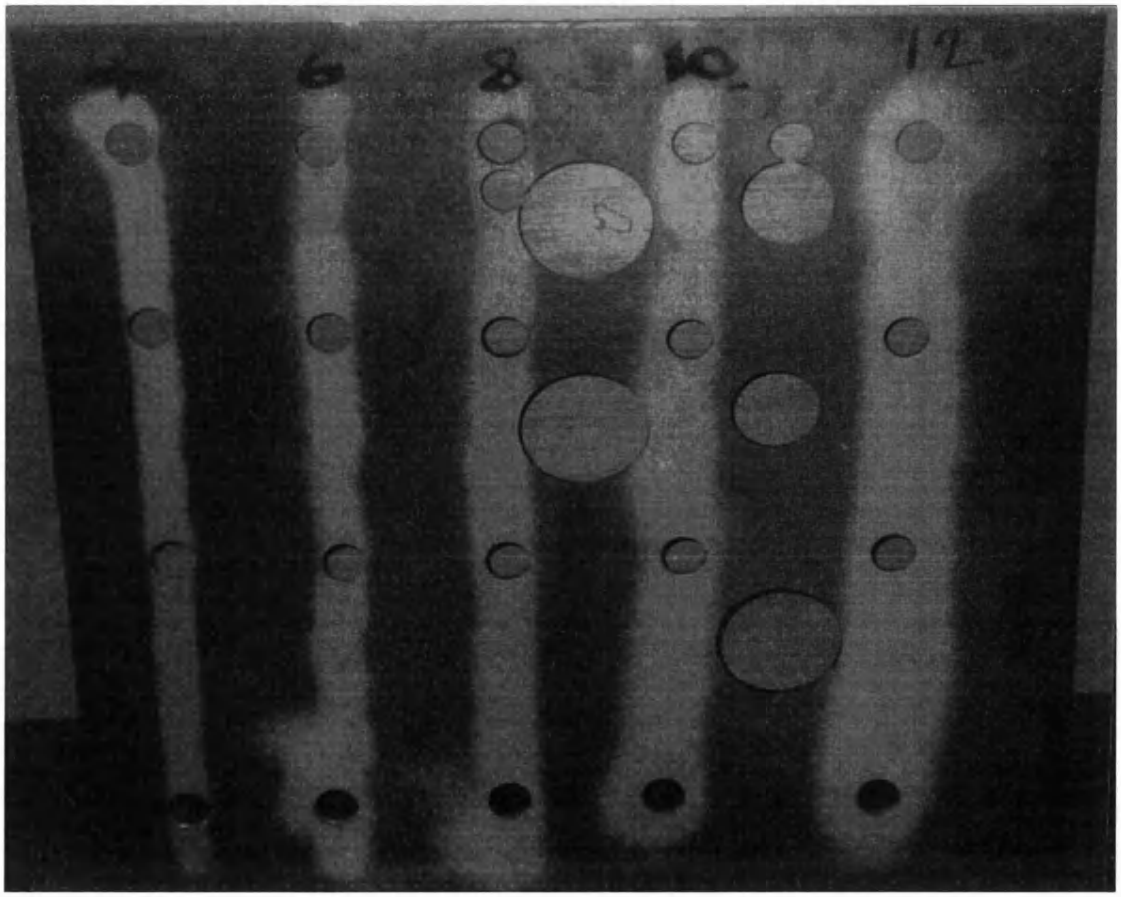
*** Vickers hardness tests were conducted with a 10kg load and measured with a 2/3" objective. Figures given are the mean of six tests ranging for mild steel 146 Hv to 159 Hv, for stainless steel 220 Hv to 242 Hv, and for aluminium 84 Hv to 86 Hv.

capable of removing up to ~35 % (2.11 mm) of the mild steel plate section, nearly 50 % (2.9 mm) of the stainless steel section and nearly 70 % (4.09 mm) of the aluminium plate thickness (see Figure 4.1d). There will be a clear trade off between material removal and surface coverage, which will need to be optimised for various contaminated surface situations. At the feed rate of ~50 mm s^{-1} it would be possible to clean just under 1 m^2 (i.e. 30 mm (blast area dia. at 150 mm stand-off) x 50 mm s^{-1} (feed rate) x 600 s (blast time) = 0.9 m^2) in approximately 10 minutes. This coverage can be more than doubled if a 300 mm stand-off is used, and both these surfaces would be left with a similar profile having been exposed within the blast zone for nominally ~1 second (i.e. 0.6 s at 150 mm stand-off and 1.2 s at 300 mm stand-off). The abrasive action that these process parameters create may remove all loose radioactive contamination and much of the fixed contamination during active trials. Nevertheless there will be situations where more material will need to be removed, for example 'hot-spots' where contamination has been embedded into the metal surface. In these cases, to obtain higher material removal, feed rates will need to be reduced to between 1.5 and 3.5 mm s^{-1} at stand-off's of 150 and 300 mm, respectively. At these feed rates surfaces will be exposed to approximately 20 seconds within the blast zone leading to the removal of between ~10 μm (mild steel) and ~500 μm (aluminium), depending on the characteristics of the waste being cleaned. Unfortunately this will reduce coverage dramatically to ~0.03 to ~0.15 m^2. If more material needs to be removed then the area will need to be treated specifically for longer periods as necessary.

Figure 4.1e shows metallographic views of the blasted mild steel surface across the time trial section comparing the abraded surface with the as-rolled plate surface. The wear or material removal rate may be influenced by hardness. The Vickers hardness of each plate

under test showed that the softest material, aluminium (85 Hv), correlated with the highest material removal rate, but the mild steel (154 Hv), with an overall microstructure that is softer than the stainless steel (225 Hv), was more wear resistant. This may be a function of the duplex phase structure (ferrite (α) and pearlite ($Fe_3C + \alpha$)) within the mild steel. Here the very hard plates of iron carbide (Fe_3C) within a soft ferrite matrix may have an overall softer structure under static loading, but under dynamic loading such as experienced under impact abrasion could be less susceptible to deformation [85]. Experience of duplex structures in the performance of bearings suggests alloys containing very hard particles exhibit improved impact and wear resistance [86].

FIGURE 4.1a: INITIAL INACTIVE BLASTING TRIALS



A view of trajectory runs from left to right at 100 mm, 150 mm, 200 mm 250 mm and 300mm. Samples were trepanned out at 90°, 70°, 50°, and 30° to the plate surface. The larger holes were for samples from the time trials on the other side of the plate.

FIGURE 4.1b: TYPICAL SURFACE ROUGHNESS RECORD FOR MILD STEEL AT 150mm STAND-OFF

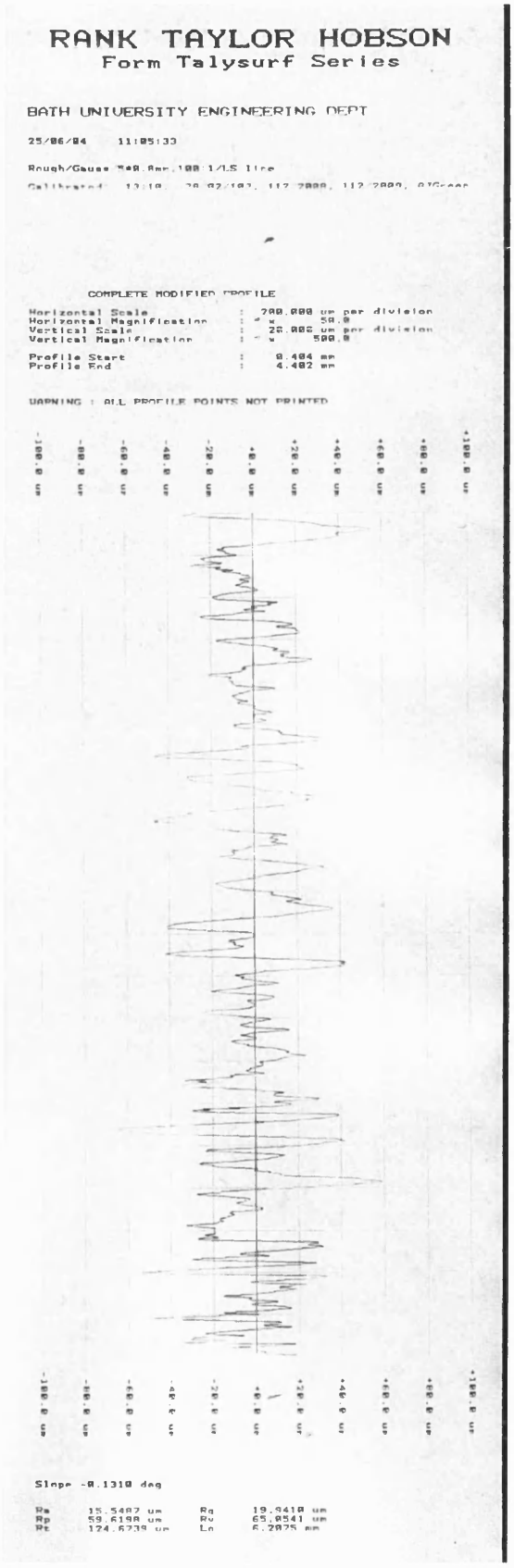
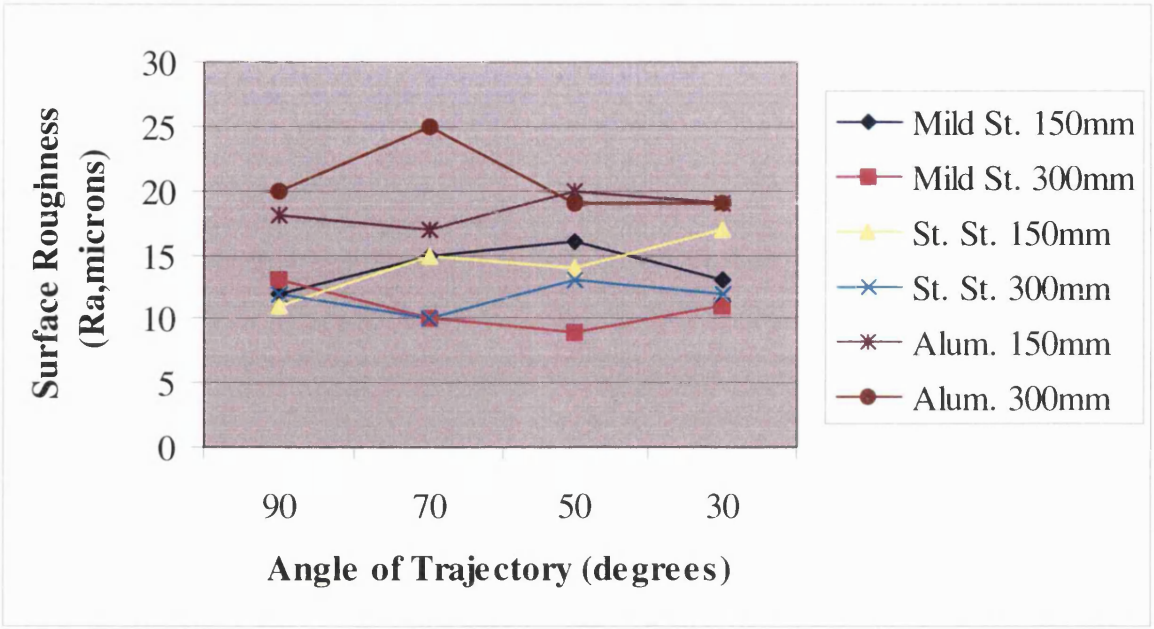


FIGURE 4.1c: NOZZLE STAND-OFF AND TRAJECTORY EFFECTS ON SURFACE ROUGHNESS



MS/Mild St. means Mild Steel Plate, St. St. means Stainless Steel Plate and Alum. Means Aluminium Plate.

FIGURE 4.1d: MATERIAL REMOVAL AGAINST BLASTING TIMES

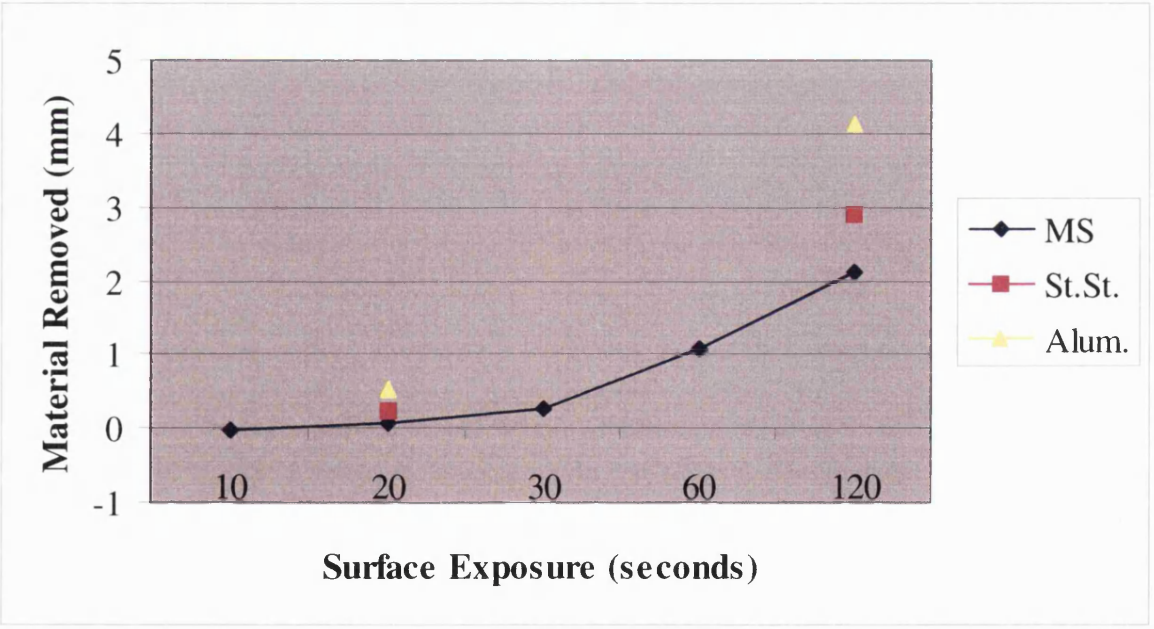
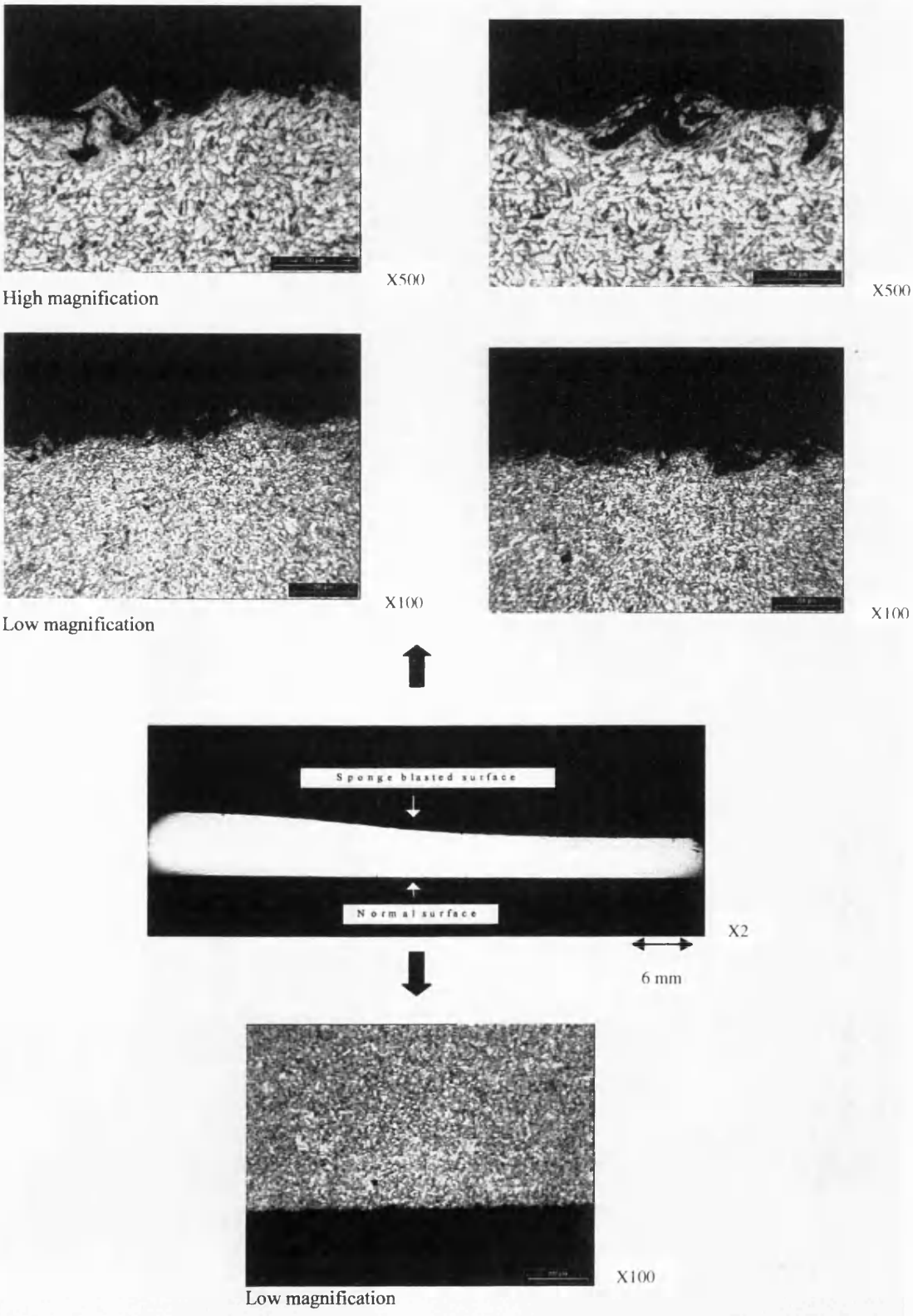


FIGURE 4.1e: METALLOGRAPHIC SECTION THROUGH THE BLAST ZONE ON MILD STEEL



It should be noted that there was no evidence of entrainment of abrasive grit or other contaminants in to the abraded surface, despite the prolonged impacts at the same site.

Non-abrasive media trials showed a slight profiling effect at the maximum blasting conditions under trial. This media did not create any surface profiling when the pressures were reduced.

4.1.2 Media Recycling

Media recycling trials were conducted and the results are summarised in Table 4.1b. The trial was conducted at maximum blast pressure (70 psi line pressure to nozzle) and at a 150 mm stand-off and at a 90° trajectory to the surface of the mild steel plate. Between passes through the blasting process the collected media was fed into the 'as-supplied' sieving machine. This separates fine broken bits of media (both PU sponge bits and bits of released abrasive as well as material abraded from the metal surface) from the media that is still intact and large enough for reuse. The sieve sizes are mesh 2 and 16. At maximum blasting conditions one 23 kg bag of Silver media provided approximately 7 minutes of blasting time in the first pass. Recycling the one 23 kg bag of abrasive media five times gave a total blast time of ~20-21 minutes and a total abraded surface area of nearly 1.2 m^2 (feed rates were not maintained at a constant rate – but the 600 mm x 600 mm plate was treated just over three times). The media collected for recycling was weighed using a load cell before being reused. This revealed losses of just over 20 % after each cycle. Since the bulk density of the media is 535 kg m^{-3}, one 23 kg box of Silver media equates to approximately 0.043 m^3. The 240 ltr capacity of the Sponge-jet blasting system will permit five 23 kg boxes (115 kg) of media to be loaded to the pressure vessel, leading to a potential first pass blast time of ~35 minutes. If recycled

TABLE 4.1b: SUMMARY OF INACTIVE MEDIA RECYCLING DATA

Blast Pass*	Blast Time (secs)	Approx.Area Covered(m^2)	Media weights (kg)#			Particle Weights (g)#[2]		
			Reusable After Pass	Waste Fines	Misc. Losses	As -received	Graded-reusable	Waste Fines
As-received	n/a	n/a	23.0	0	0	≤ ~0.1	-	-
1	420	0.4	~18.1	~4.5	~0.6	-	0.005 to 0.08	≤ ~0.0015
2	330	0.32	~14.3	~7.8	~1.2			
3	240	0.23	~11.3	~10.3	~1.8			
4	150	0.14	~8.9	~12.3	~2.4			
5	105**	0.1	~7.0	~15.0	~3.0#[1]			
Totals	1245	1.19						

* A single 23kg bag of Al oxide impregnated 'Silver Media' was blasted at maximum blasting conditions on to a mild steel plate at a 150mm stand-off, for five recycles through the total as-supplied process.

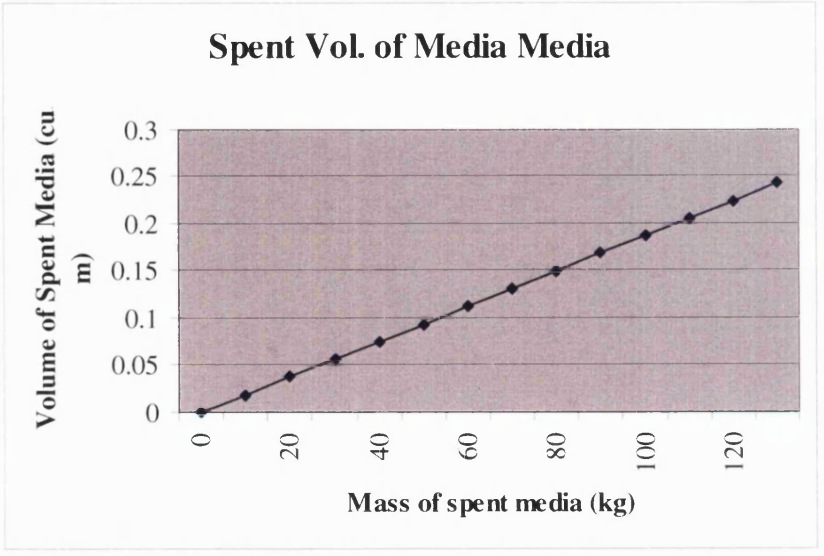
** Blast times were estimated based on sound of media coming through the nozzle and when it stops. On the fifth pass the start and stop points were becoming difficult to clearly define due to the limited amount of media available.

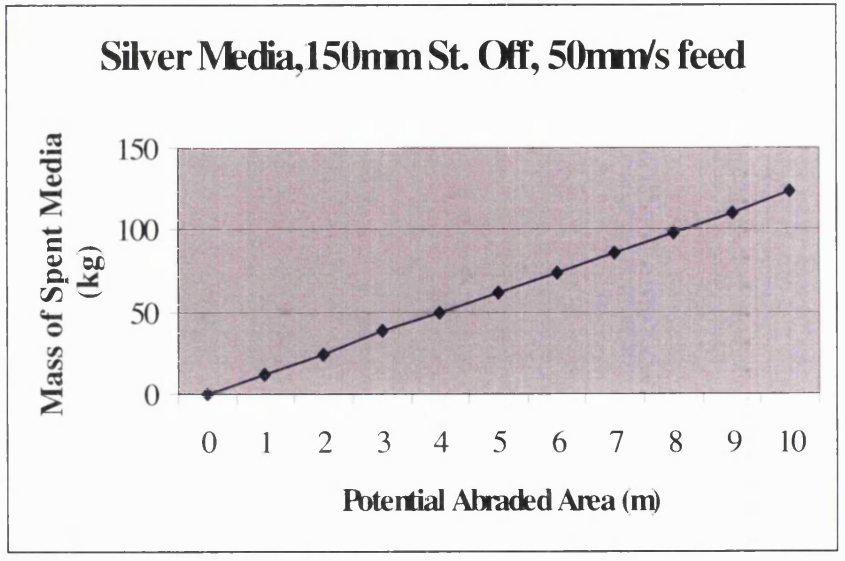
Media weights were measured after the suppliers grading process had been carried out between each pass, using a load cell and are presented cumulative values.

#[1] After the trial and dismantling of the tent/containment some media was found in the folds of the PVC (~3.03 kg), so these losses have been proportionally spread over each pass leading to an estimated error of ~2.6% for reusable media and waste fines at each pass. Cumulatively this leads to approximately a 14% error for reusable media and 28 % error for waste fines after 5 passes. The error on the waste fines is slightly higher to allow for abraded waste fines from the metal surface.

#[2] Samples of media were taken after each stage in the process. Random numbers of particles were selected from as-new, recycled and reusable and waste unusable fines, examined using a macroscope (see Figure 4.1h) and weighed using digital scales (accurate to 4 dps).

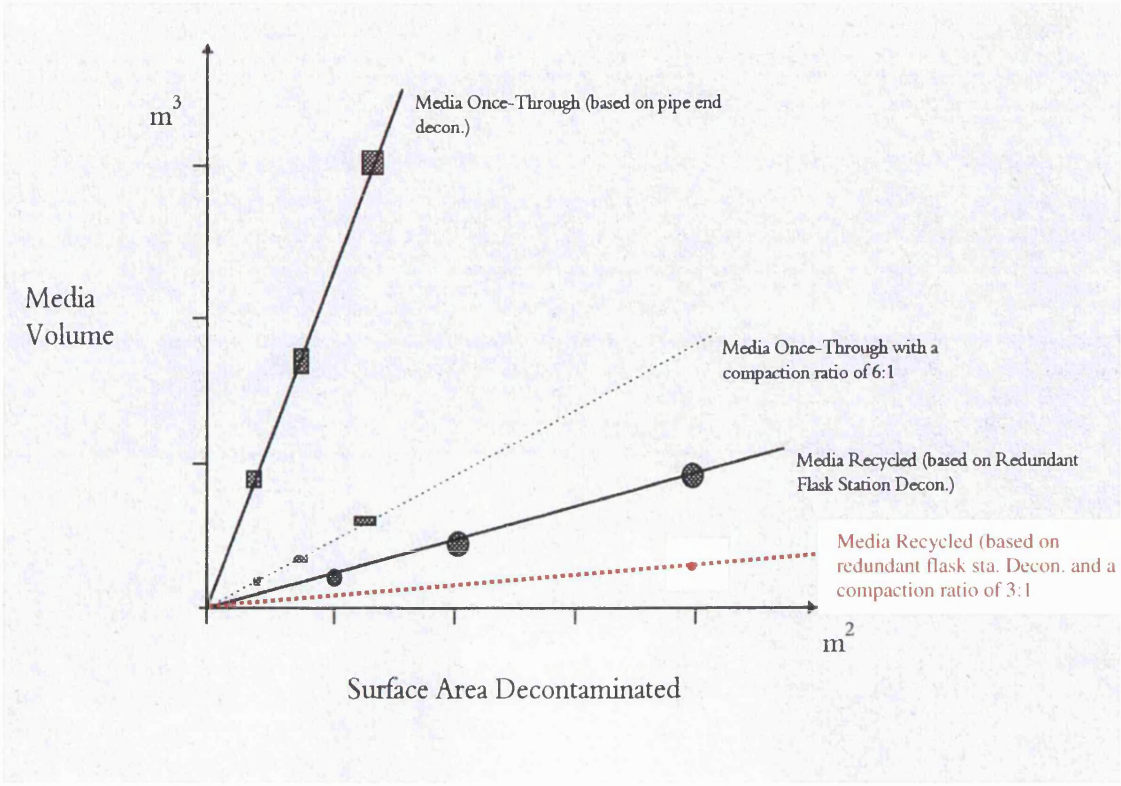
FIGURE 4.1f: POTENTIAL SURFACE AREA DECONTAMINATION FOR GIVEN SPENT SPONGE MASS AND VOLUME





NB. Sponge media can be volume reduced by compaction and new media has been reduced in volume up to 6 times. Clearly as the sponge is recycled it breaks up into smaller particles that will effectively reduce the bulk volume of the sponge for disposal, but it is still possible that a further compaction of up to say ~3 times could be achieved. So 100 kg of spent media would be reduced from a non-compacted volume of 0.19 m^3 to as little as 0.06 m^3.

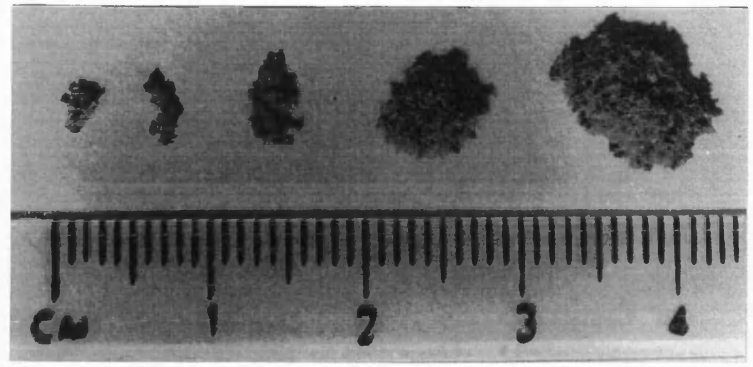
FIGURE 4.1g: A COMPARISON OF MEDIA VOLUME AGAINST SURFACE AREA CLEANED



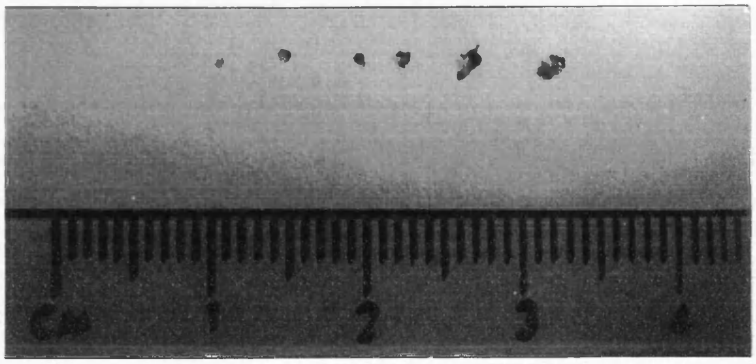
using the same parameters (at 150 mm stand-off and a feed rate of 50 mm s^{-1}) used in this trial potentially 1hr and 44 minutes (103.75 mins) of blasting time could be achieved with the ability to clean or scour 9.34 m^2 at a 150 mm stand-off (or 21.79 m^2 at a 300 mm stand-off). Figures 4.1f and 4.1g summarise the implications of this process performance in cleaning waste material. Clearly each waste decontamination problem should be evaluated upon its own merits, but in order to assess whether this technology can do the job without producing a larger waste volume than has been cleaned, the break even or cost-benefit point needs to be established.

Assessment of samples of media taken after the grading process shows that particles which weigh more than ~1.5 mg are recycled, while the fine unusable particles are

FIGURE 4.1h: MACRO-EXAMINATION OF REUSABLE AND WASTE SPONGE MEDIA



Good Reusable Media



Spent Media

TABLE 4.1c: PARTICLE DIMENSIONS AND WEIGHTS FOR REUSABLE AND WASTE SPONGE MEDIA

Sample Status	No. of Particles	Mean Weights (mg)*	Dimensions (mm)
Green - as received	52	15.7	2 – 15
Silver - as received	59	38.3	2 – 15
Sil - ungraded, pass 1	169	5.4	<0.5 – 12
Sil - graded, reuse, pass 1	35	33.2	~2 – 10
Sil – graded, waste, pass 1	149	0.5	<0.5 – 1.5
Sil - graded, reuse, pass 2	30	31.5	~2 – 9
Sil – graded, waste, pass 2	30	1.3	<0.5 – 1.5
Sil - graded, reuse, pass 3	30	11.0	~2 – 9
Sil – graded, waste, pass 3	30	<0.5	<0.5 – 1.5
Sil - graded, reuse, pass 4	30	3.4	~2 – 9
Sil – graded, waste, pass 4	30	<0.5	<0.5 – 1.5
Sil - graded, reuse, pass 5	30	2.3	~2 – 9
Sil – graded, waste, pass 5	30	<0.5	<0.5 – 1.5

* Petri-dish cleaned and weighed first, then samples poured into dish and weighed. The particles were then counted out of the dish up to pass 1, for pass 2 to 5, 30 particles were selected at random and counted into the dish.

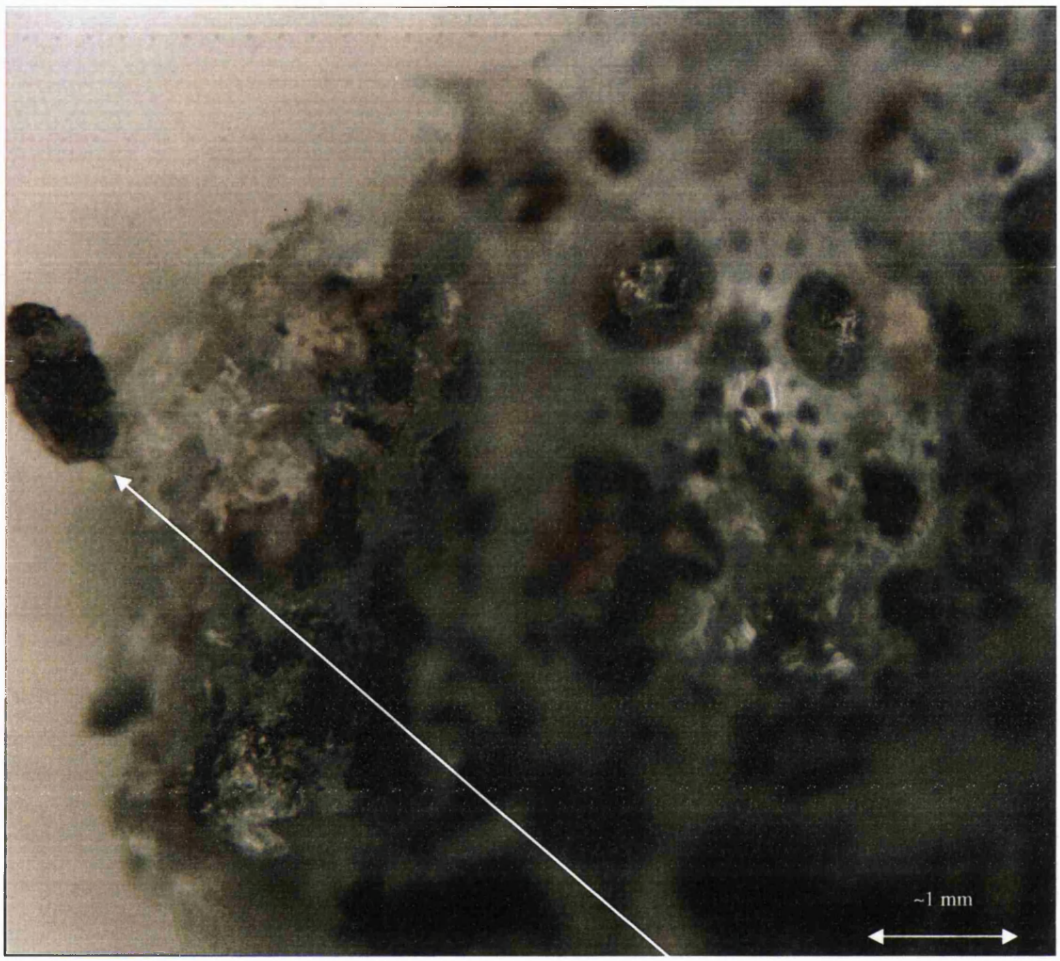
generally below 1.5 mg in weight. Macro examination (see Figure 4.1h and Table 4.1c) shows that these particles can be split at the 1.5 mm maximum dimension, where unusable particles are usually <1.5 mm across, and reusable particles are >1.5 mm across their maximum dimension.

Particles were sampled from both the reusable and waste fines for more detailed examinations under both macroscope and microscope. Figure 4.1i shows a recycled particle and some spent fines. The lack of an adequate depth of focus restricts detailed examination of the particle, but the break up and loss of abrasive grit is clear. Study of the spent fines confirms that the recycled media is losing its abrasive grit and metal filings cut by the abrasive can be seen in the waste fines. These have been cut from the metal surface by the aluminium oxide grit in the sponge particles. It was unclear what mechanisms were responsible for the sponge particles holding on to contaminants and giving rise to low airborne dust contamination. Figure 4.1j reproduces still frames from a Sponge-jet promotional video that shows in slow motion how the particles pull black soot from a fire-damaged surface [3]. This suggests that the sponge media tends to retain the contaminant rather than spreading it about or making it airborne. It appears that the particles collapse on impact and the surface contaminants stick to the particle as it recoils and returns to its sponge form. The particle spreads out on impact, then on recoil constriction of the impact face may assist a gripping action. Pneumatic effects may play a part in keeping airborne contaminant levels down as the open cells of the sponge particle reform. To study these effects further and the mechanisms involved a number of sponge particles were mounted in a thin resin that impregnated the open pores/cells of the media. Once the mount was cured the specimen was prepared metallographically using silicon carbide papers and diamond polishing [87]. Figure 4.1k shows that the particles do retain

fine metal particles within the pore structure of the particle body, suggesting this pneumatic effect contributes some way to minimising the generation of airborne contamination or fine dust. The sponge has in effect a level of absorbency during the impact process which helps to keep airborne contamination levels down [88]. The last plate in Figure 4.1k shows the first stages of the alumina grit break up. This grit particle is still retained by the polyurethane foam but appears to have a fracture forming on the side. This also appears to be holding on to fine filings of metal abraded from the plate surface. Alumina grit is well known for being an excellent abrasive, the brittle fracture of the grit reveals new sharp edges that facilitate further efficient cutting, whereas more ductile or malleable grit does not fracture in a brittle way and its sharp edges become blunted after impact. The presence of loose contaminants in the spent fines shows that the particles lose this material as they are vibrated during grading. This suggests that the recycling of the media may not re-entrain contamination back onto the next surface to be cleaned.

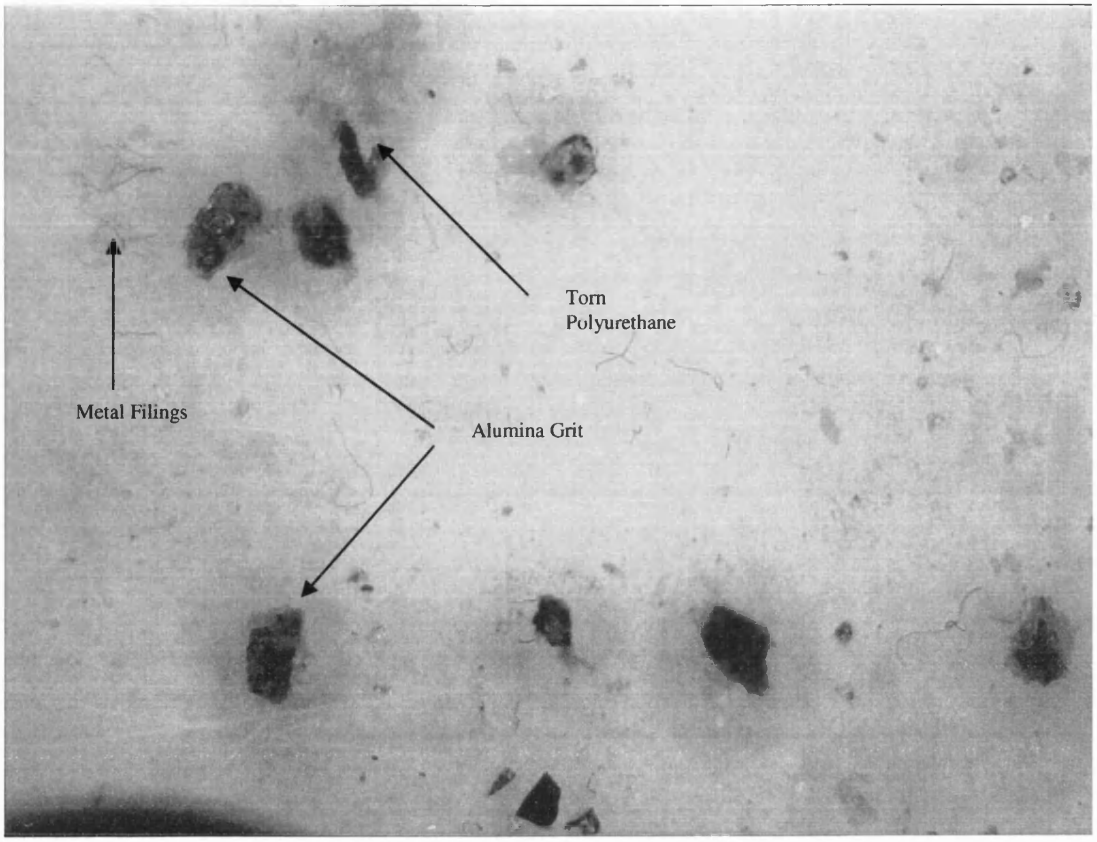
FIGURE 4.1I: MACROSCOPE EXAMINATION OF REUSABLE AND SPENT MEDIA FINES AFTER GRADING

Reusable Particle



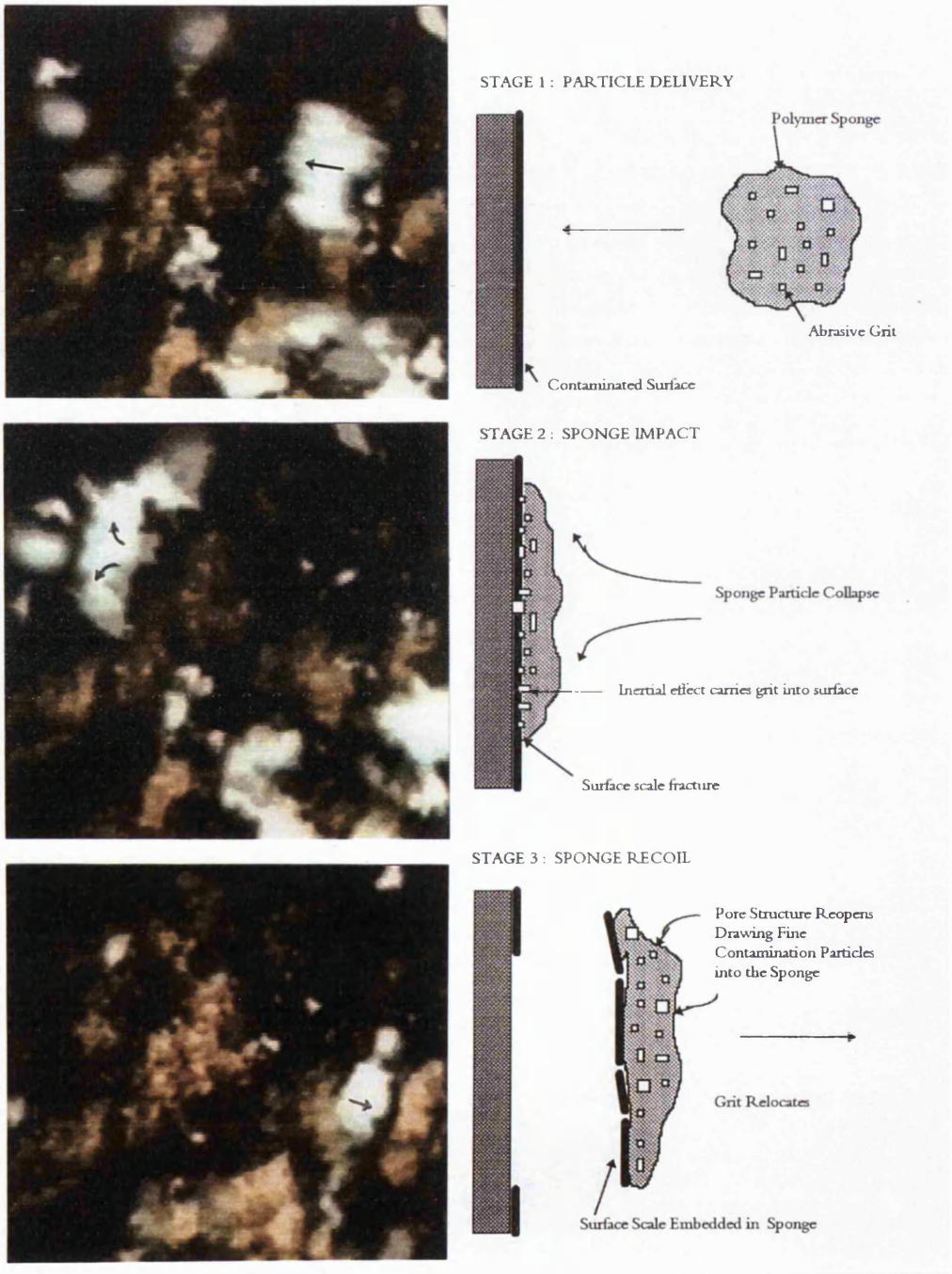
Macroscope examination of the recycled media shows grit particles becoming detached

Figure 4.1i Continued
Fines



Spent fines showing lost alumina grit, pieces of torn polyurethane, and metal filings from the inactive trials on metal plates

FIGURE 4.1j: NON-ABRASIVE GREEN MEDIA REMOVING BLACK SOOT CONTAMINATION



(Slow motion stills reproduced from suppliers promotional video courtesy of Sponge-jet UK)

FIGURE 4.1k: SILVER MEDIA IN CROSS-SECTION REVEALING CONTAMINANT TAKE UP IN OPEN CELLS OF THE SPONGE

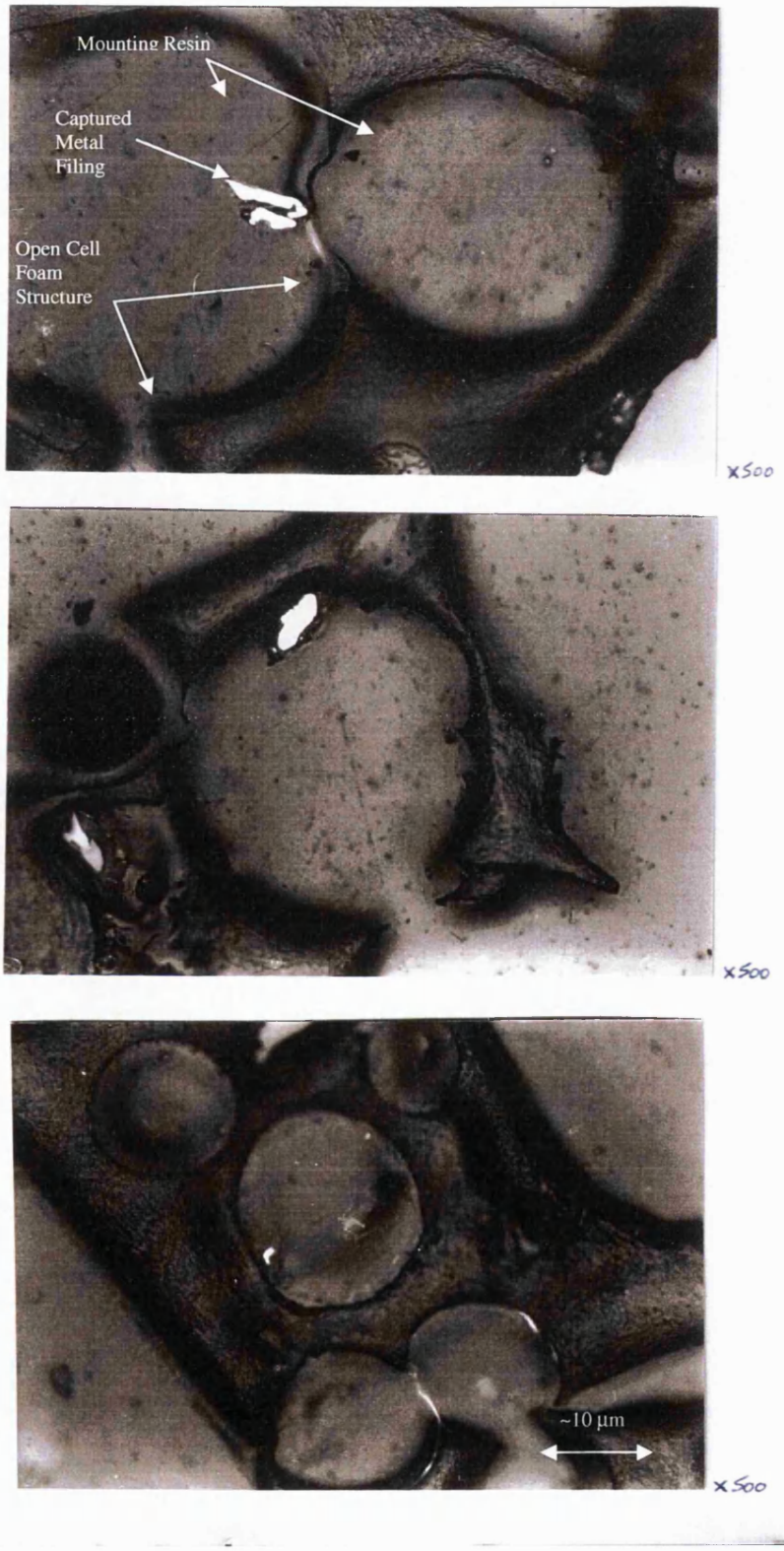
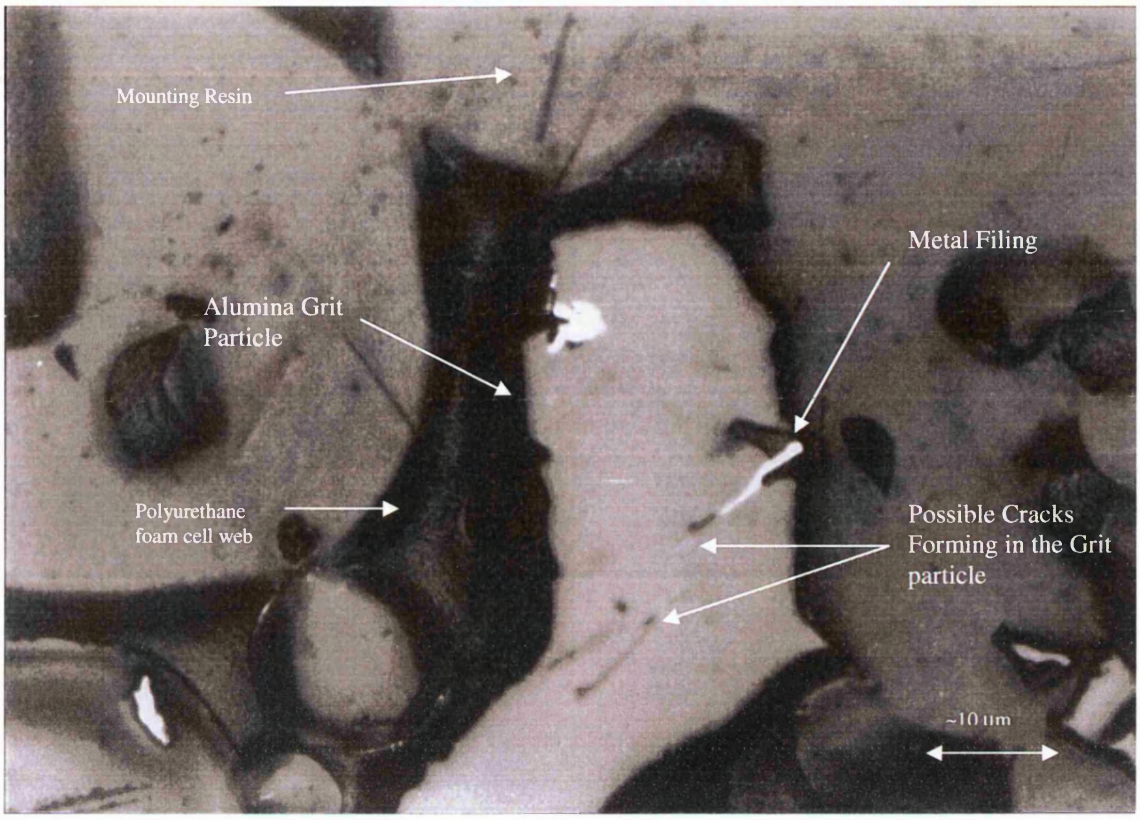


Figure 4.1k. Continued



Aluminium grit particle in cross section with the suggestion of a crack forming that has cut a piece of metal filing from the plate surface – still held within the crack

Further studies using a scanning electron microscope (SEM) were undertaken on samples taken during the inactive recycling trials [89], in order to further study their morphology and examine the effects of the blast and impact conditions upon the sponge media. Both Silver abrasive and Green non-abrasive media were examined in the as-new state, while the Silver media was further studied in various recycled states. The samples were prepared for the SEM examination using Silverdag® to attach a selection of media particles to an aluminium stub. The samples were then sprayed with a carbon suspension to allow conduction from the surface of the insulating media particle to the specimen holder. These initial trial samples were examined using a Leica S440 SEM. Preliminary investigations on the as-new material were carried out using an accelerating voltage of

10 kV to minimise the chance of electrical breakdown. Later it would be necessary to take X-ray spectra at 20 V, however, this did not appear to cause excessive charging or damage to the sponge particles.

Figure 4.11 shows observations of a Green media particle. The non-abrasive sponge media consisted of fairly smooth regions interrupted by pore cells up to 100-200 μm in diameter. Some pores or cells were clearly interconnected and represent an artefact arising from the foaming and curing stages of manufacture of the sponge. Across the surface of the sponge cells were some loose rounded and many loose fibrous particles. The rounded particles were typically 2-6 μm across, while the fibrous particles were typically 5-40 μm in length (although one fibre was 150 μm long). Figure 4.1m shows the typical X-ray spectrum for the polyurethane, and each surface particle. These show that the particles contain mainly Calcium (Ca), Oxygen (O) and Silicon (Si), with the rounded particles being lower in Ca than the more fibrous particles. The rounded particles also contain some Aluminium (Al) that is not present in the fibrous material. This appears to be consistent with the materials data sheets provided by the Sponge-jet suppliers showing that the Green media contains Wollastonite (69-83 %), Diopside (0.1-0.8 %), and Garnet (0.3 %) [57]. Wollastonite is a mineral that is commonly formed in metamorphic geological situations in the contact zone with calcite and quartz intrusions in limestone formations [90]. Wollastonite or Calcium Silicate forms through the chemical reaction as follows:

$$CaCO_3 + SiO_2 \Rightarrow CaSiO_3 + CO_2$$

FIGURE 4.1l: SEM MICROGRAPHS OF AN AS-NEW GREEN NON-ABRASIVE SPONGE PARTICLE

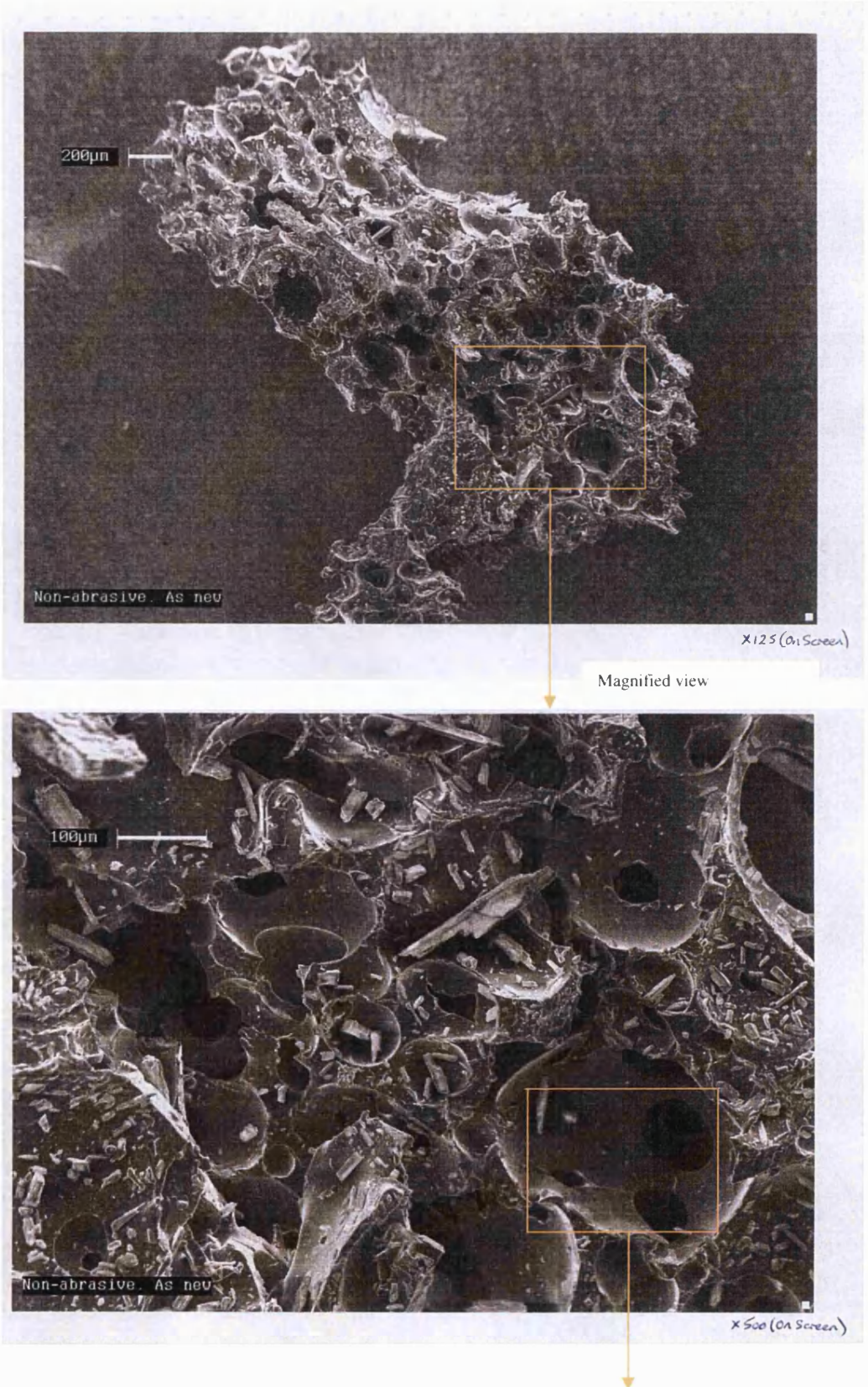
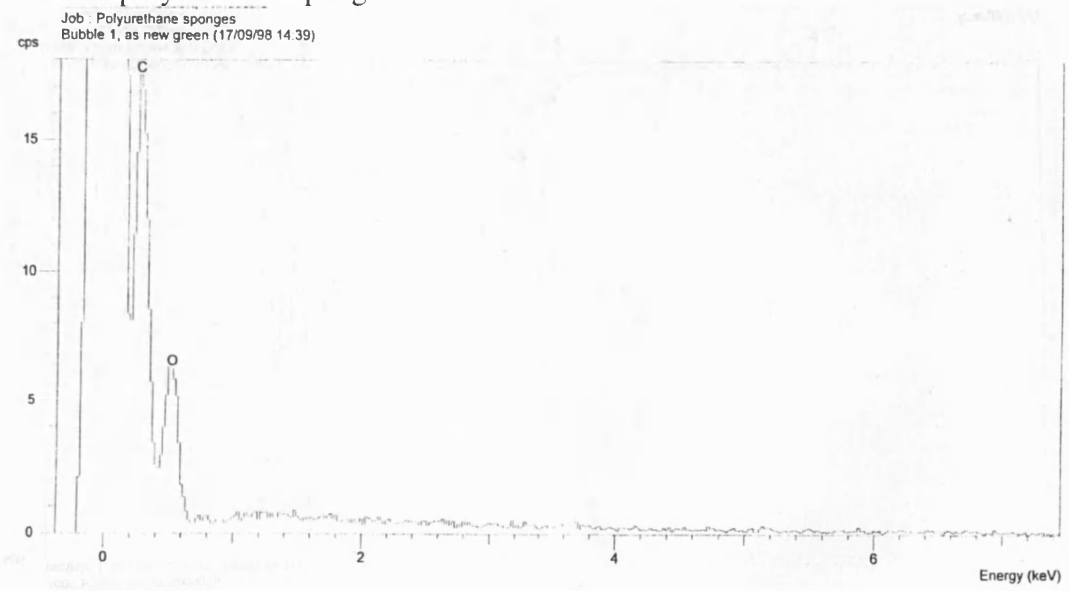


Figure 4.1l Continued

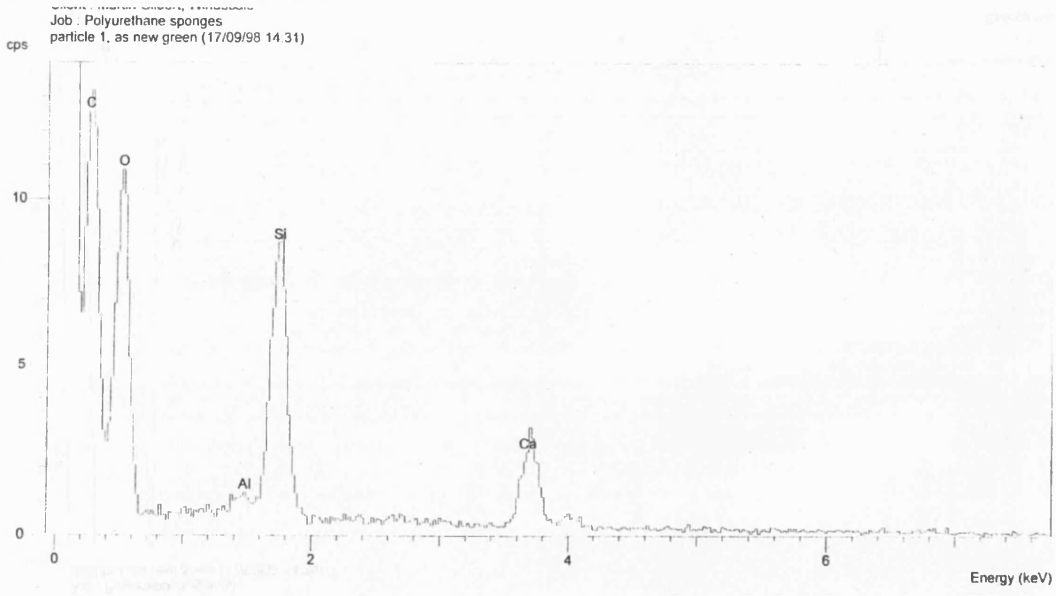
Note the open cells and the linkages, the rounded and fibrous particles

FIGURE 4.1m: X-RAY SPECTRUM FROM GREEN NON-ABRASIVE MEDIA

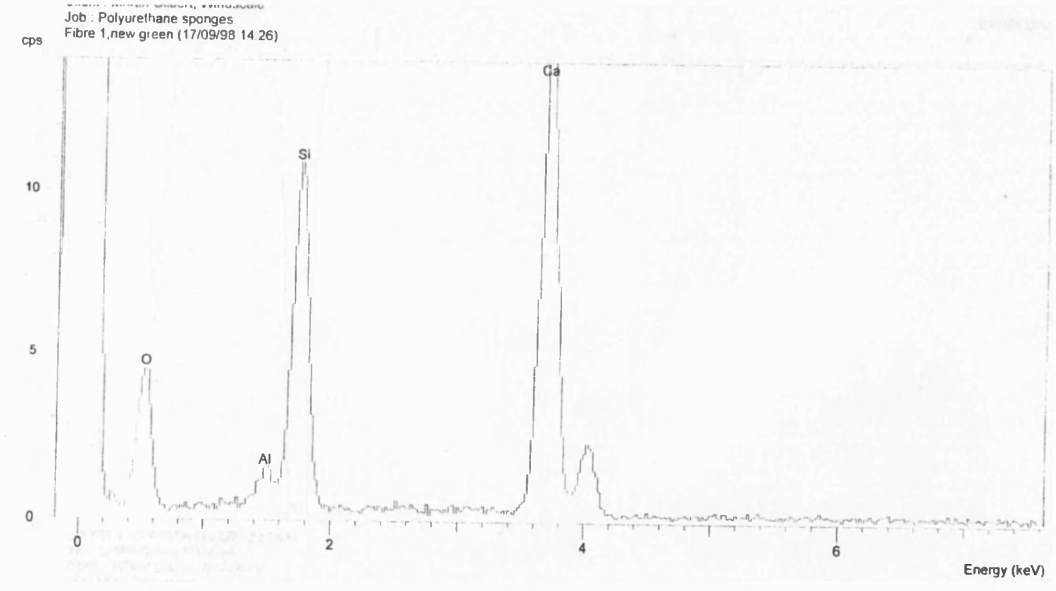
From the polyurethane sponge



From rounded particle



From fibrous particles



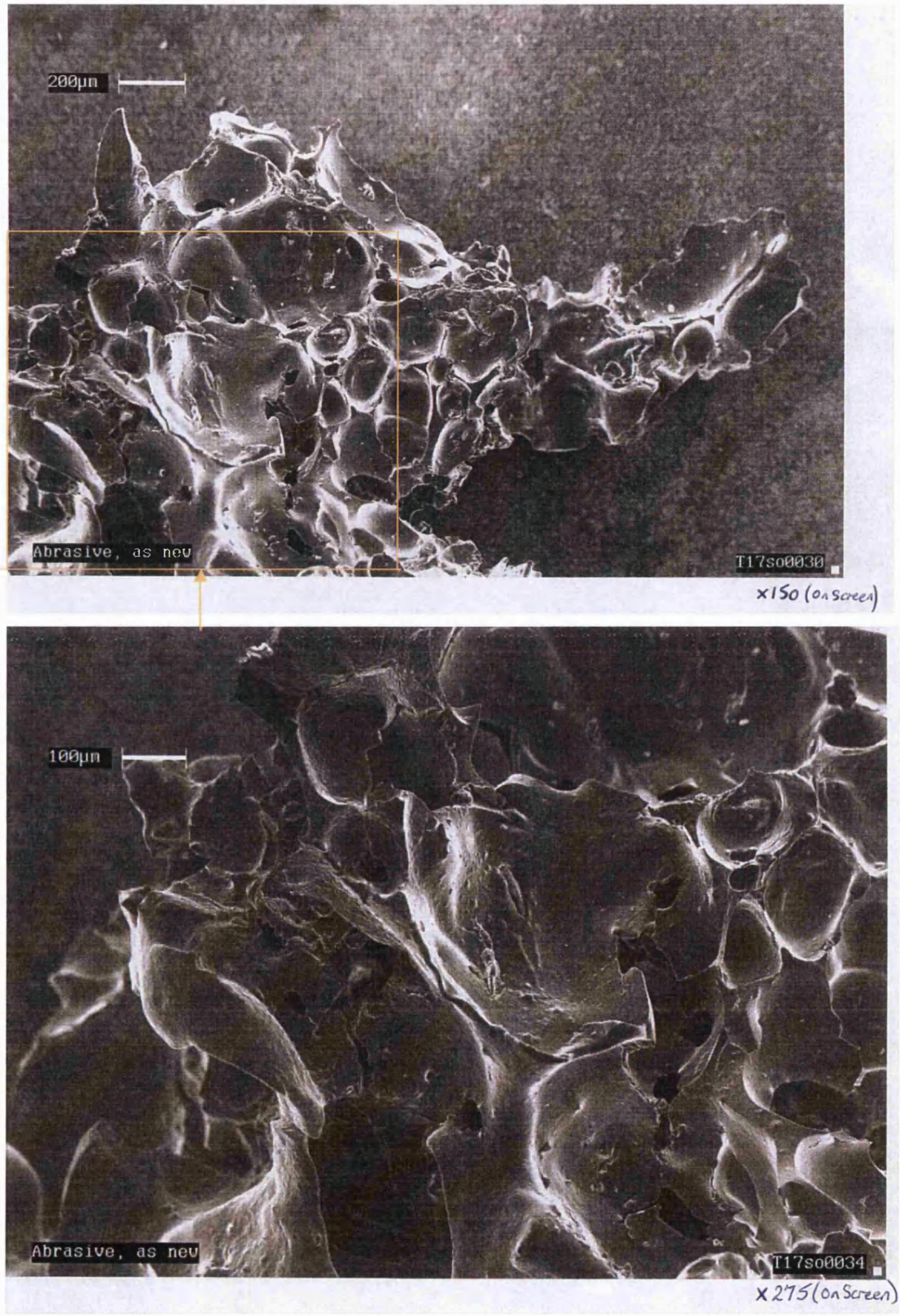
Wollastonite often forms in radial fibric masses that cleave readily in to splinters. This mineral is also associated geologically with other minerals, e.g. Diopside and Garnet which is why they are included in the material data sheet. Wollastonite is used in talc,

paints, tile manufacture and some metallurgical processes (e.g. welding) [90]. It is unclear why this mineral is used as an additive to the Green media, and it does not appear to have been added during the polyurethane sponge-manufacturing phase. It may have been added to the media at the chopping stage in order to minimise clogging, or provides some form of benefit during the wiping action when cleaning surfaces e.g. lubrication to minimise drag and prolong particle life.

The Silver sponge media was also studied in the as received (new/unused) condition, and like the Green media exhibited some variability in pore/cell size (up to ~200 μm across), and a degree of pore connectivity (open cells). Figure 4.1n shows 'as-new' Silver abrasive media with embedded Al oxide particles. Figure 4.1o shows X-ray spectrum of the sponge and various grit particles embedded in the polyurethane sponge. The pore/cell surfaces appear smooth with occasional pockmarks, and markedly clear of debris compared to the 'as-new' Green media. Embedded grit particles could be identified despite the carbon coating. Most grit under X-ray analysis was found to be mainly Aluminium oxide (AlO and or Al_2O_3) with some Titanium (Ti), Silicon (Si) and Iron (Fe). One grit particle was found to be Fe rich rather than Al rich. This may be a result of cross contamination during the manufacturing process. Some particles appeared well bonded into the polyurethane matrix, while others appeared to be less well bonded to the plastic. Some particles appeared to exhibit a coating, which may have been an artefact from specimen preparation. Discussion with Sponge-jet suppliers suggested that the grit might have been pre-coated prior to mixing with the polymer during manufacture of the sponge media to assist in the bonding process [7].

[7] Private communication in 1999 with Mr A Wilks (Sponge-jet UK) regarding the pre-treatment of abrasive.

FIGURE 4.1n: SEM MICROGRAPHS OF AN AS-NEW SILVER ABRASIVE SPONGE PARTICLE

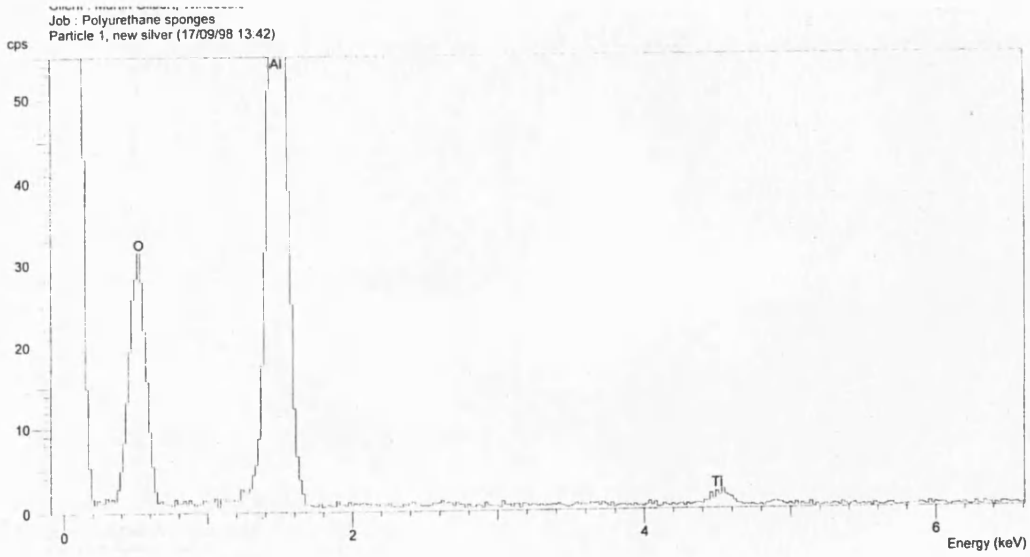


A view of brand new Silver media – note the smooth surfaces and lack of debris

Figure 4.1n. Continued

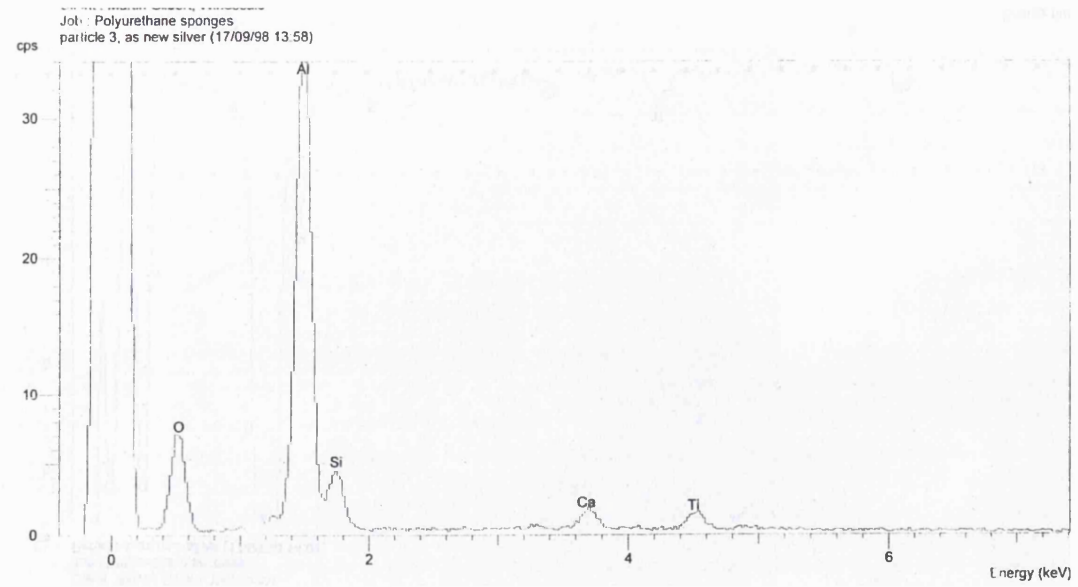
Large alumina grit particle (200-300µ across) embedded in the polyurethane media

FIGURE 4.1o: X-RAY SPECTRUM OF VARIOUS GRIT PARTICLES IN SILVER ABRASIVE MEDIA

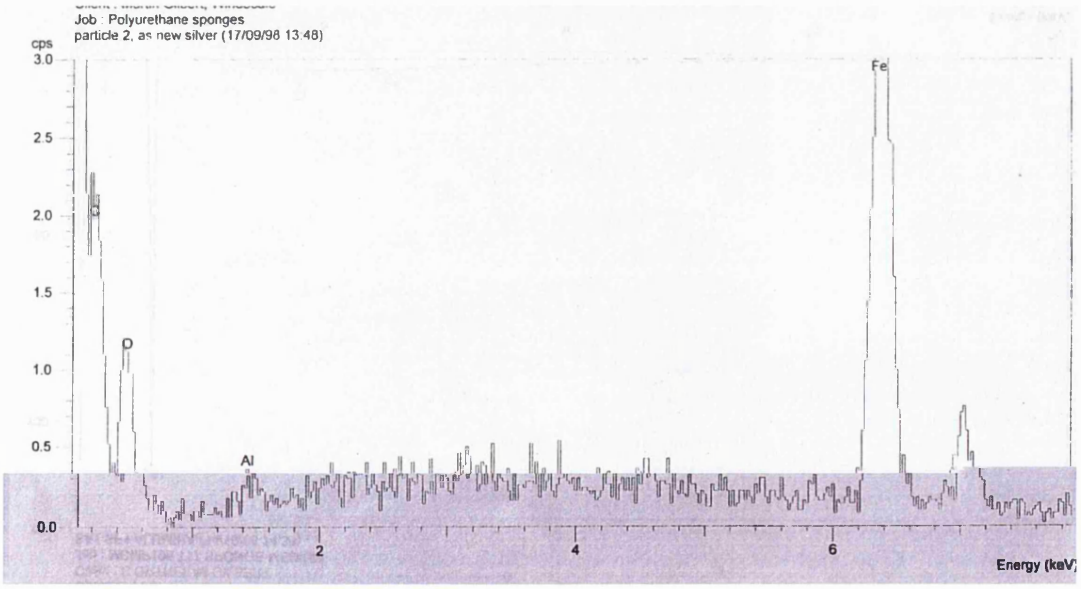


Predominantly an aluminium rich particle with some titanium

Figure 4.1o. Continued



Aluminium rich particle with some silicon, calcium and titanium components



A predominantly iron rich particle

Figure 4.1p and 4.1q show particles that have been recycled three and five times, respectively, and the effect that repeated blast impacts have had on the media. Clearly the polyurethane sponge particles break up during recycling, as observed by the increase in waste fines and reduction in the size of the remaining reusable sized particles. These examinations show that the aluminium oxide grit particles are fracturing on impact during successive blasting operations. In stark contrast to the 'as-new' media the sponge surfaces were covered in debris. Some particles were found sited near to structural damage in the sponge material. This damage often took the form of cuts or tears in the polyurethane that sometimes went completely through the webs between pores/cells (see Figures 4.1p(plate a) and Figure 4.1q(plate d)). In some instances the grit particles are still sited at their original embedded position within the sponge showing significant fracturing. Cuts or tears can be seen in the adjacent polyurethane leading away from the fracture point on the particle (see Figure 4.1q (plate b)). Many of these cuts or tears are very clean showing no signs of plastic deformation. The effect of fracturing and the inertial effect of the heavier grit particles within the lighter polyurethane sponge may be causing this structural damage to the sponge particles. On one rare occasion an enclosed crack was observed in a pore/cell web on a particle that had been recycled five times (see Figure 4.1q (plate c)). Here some 'necking' or local deformation could be observed to one side of the crack (Figure 4.1q. (plate c)), possibly as a result of successive stretching beyond the polyurethane elastic limit. The general absence of such damage suggests that this is not the main cause of particle break-up, and that the cutting effect of the grit is the primary cause of damage limiting the life of the sponge particles. Successive recycles and impacts appear to result in the grit particles either cutting their own way out of the sponge media, or eventually falling out of their polyurethane encapsulation. Silver sponge particles are therefore becoming progressively less effective at abrasively cutting

the metal surface. After approximately five recycles at maximum blast pressures there is minimal abrasive effect remaining in the media.

An assessment of particles >10-15 μm across over an approximate screen view of 1-1.5 mm^2 was carried out on a sponge particle that had seen three blast cycles and one that saw five blast cycles to compare the chemical make up and number of grit/debris particles. Table 4.1d summarises the results of this work. In both cases the particles were Al, Fe, Si or Ti rich in terms of their chemical composition. The Al rich particles also contained some traces Ti, Mg and C. Al rich particles were by far the most common, accounting for between 59 % (three cycles) and 73 % (five cycles) of all particles identified above 10-15 μm. Although less debris was identified in the area of the sponge that was recycled three times, the grit debris was generally larger in size with some particles still in-situ within the sponge. The numbers of Fe, Si and Ti rich particles identified on both particles were remarkably similar. This suggests that the fracturing of the relatively brittle Aluminium Oxide particles is giving rise to the increased number of grit particles being viewed on the sponge that saw five recycles. The relatively low number of Fe particles suggests that the particles have not retained a great deal of the steel from cleaning/abrading the steel plate after grading and handling during sampling. This supports earlier observations.

The alumina grit is likely to be what is termed 'brown' aluminium oxide which is ~95% pure containing small amounts of Titanium. This gives the grit durability compared to 'white' aluminium oxide, which is over 99% pure and is more friable [91].

FIGURE 4.1p: SEM MICROGRAPHS OF SILVER ABRASIVE SPONGE MEDIA AFTER THREE RECYCLES

Plate a: Media damage – note the grit particle appears to have sheared through the PU

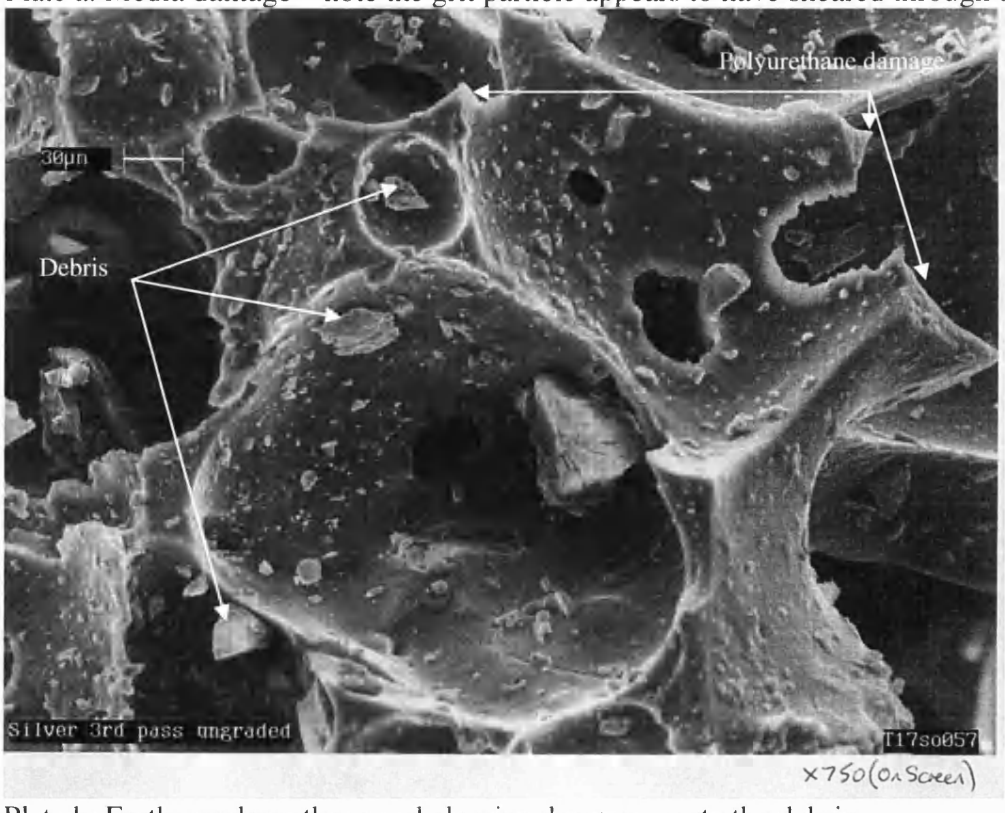


Plate b: Further polyurethane and alumina damage – note the debris

FIGURE 4.1q: SEM MICROGRAPHS OF SILVER ABRASIVE SPONGE MEDIA AFTER FIVE RECYCLES

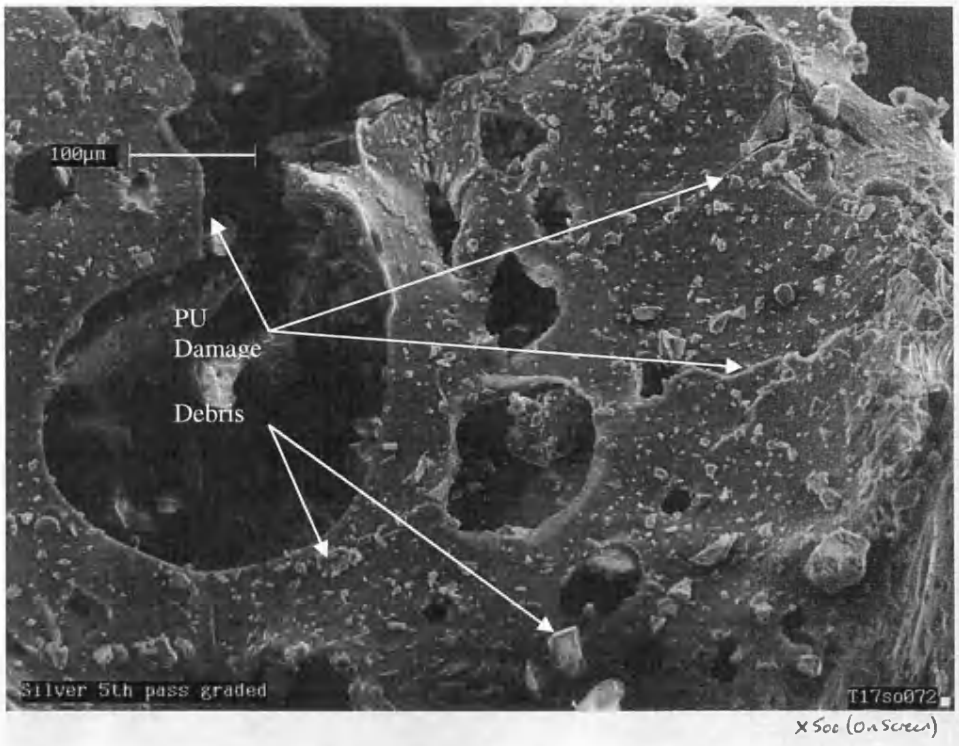


Plate a: note the level of debris over the surface of the polyurethane

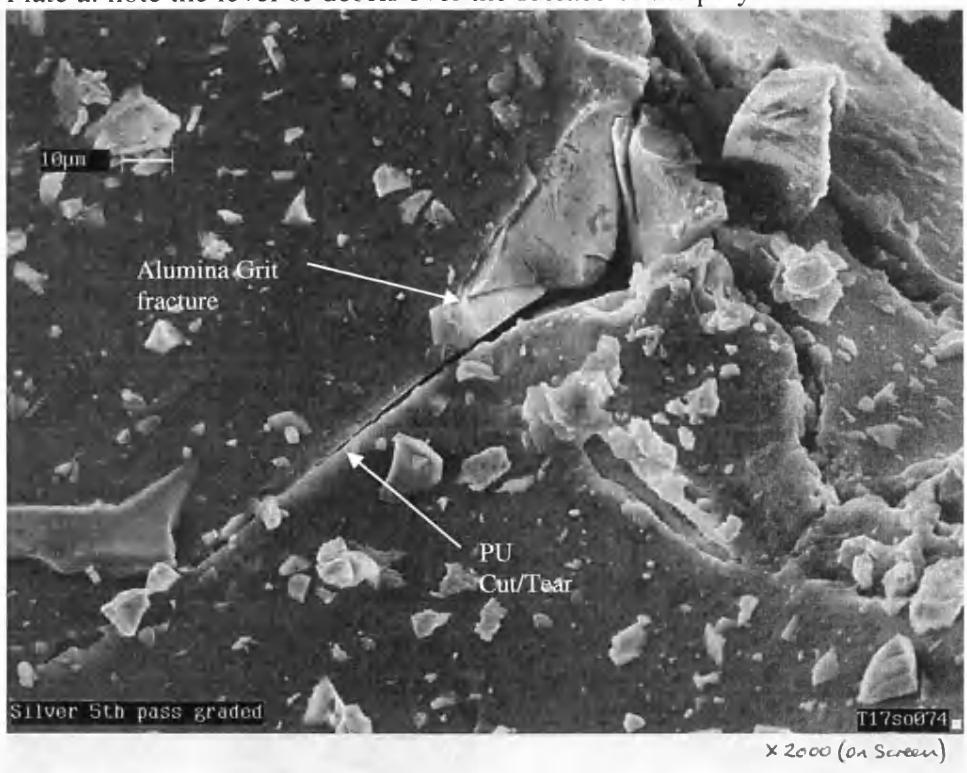


Plate b: Further damage – note the association of alumina grit fracturing and polyurethane damage

Figure 4.1q. Continued

Plate c: Enclosed crack in polyurethane web and distortion to right of fissure

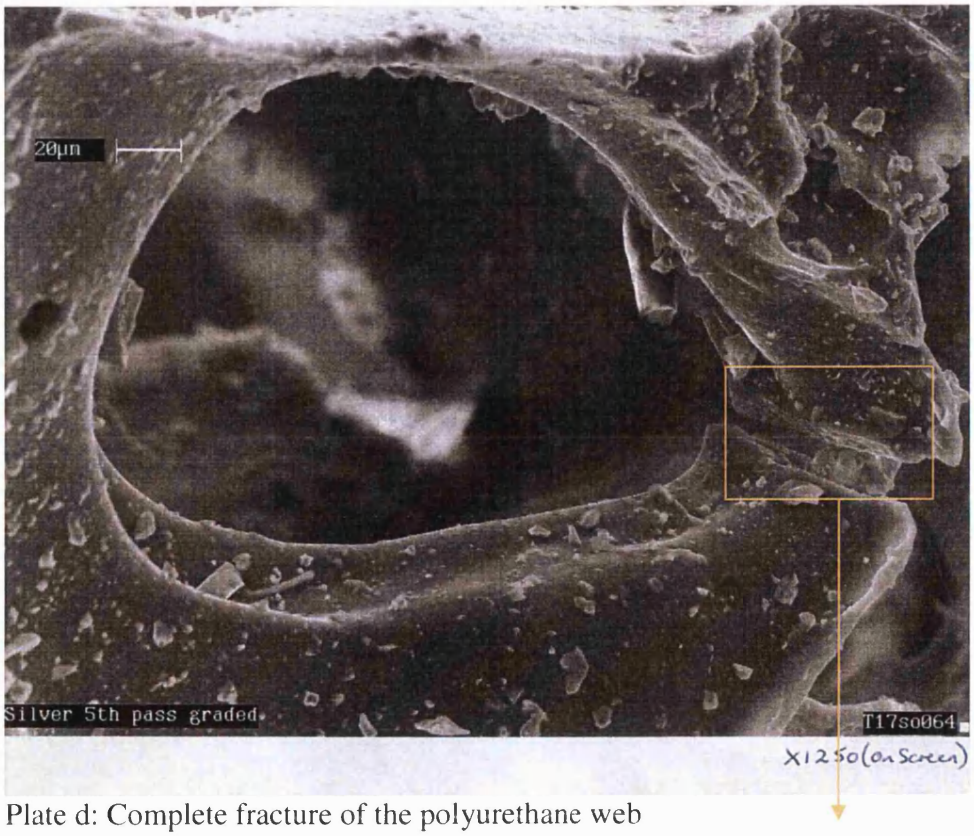


Plate d: Complete fracture of the polyurethane web

Figure 4.1q. Continued

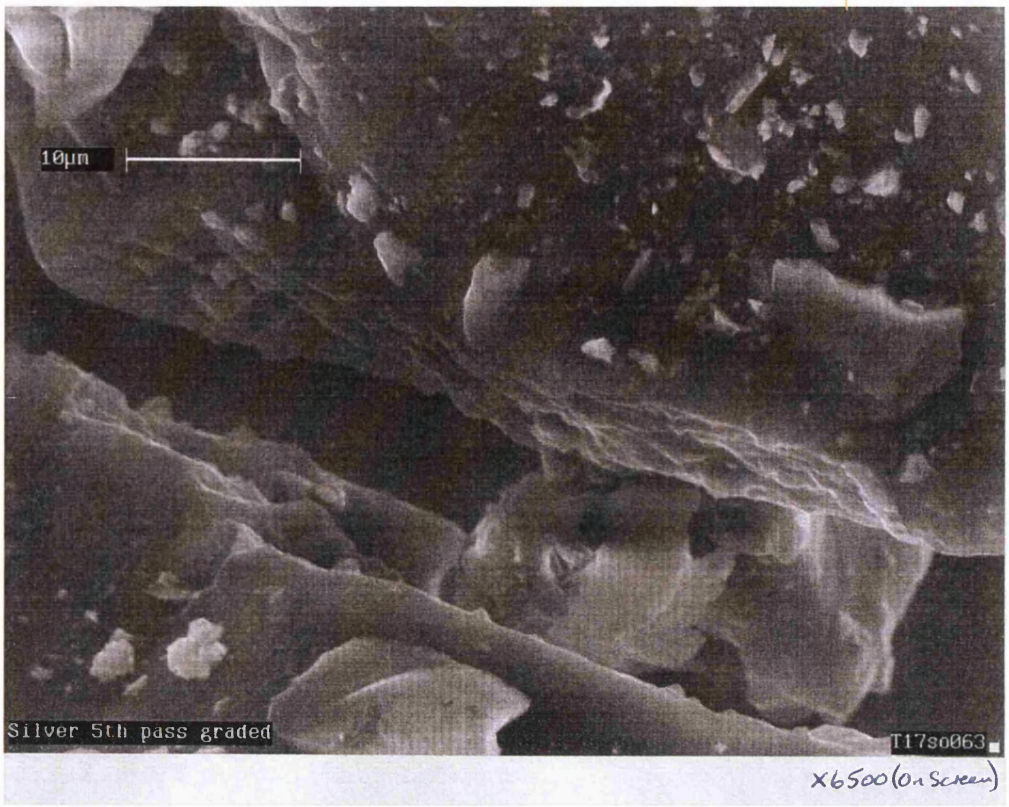


Plate e: Detail from plate d, showing grit particle between fracture faces of the web

Due to timescale and resource constraints it was not possible to conduct a full particle size analysis, however a larger number of particles were assessed to analyse their main constituents and Table 4.1d attempts to give a feel for the relative proportion of each type of particle.

TABLE 4.1d: PROPORTIONS OF DIFFERENT PARTICLES FOUND IN ON SILVER MEDIA PARTICLES AFTER USE

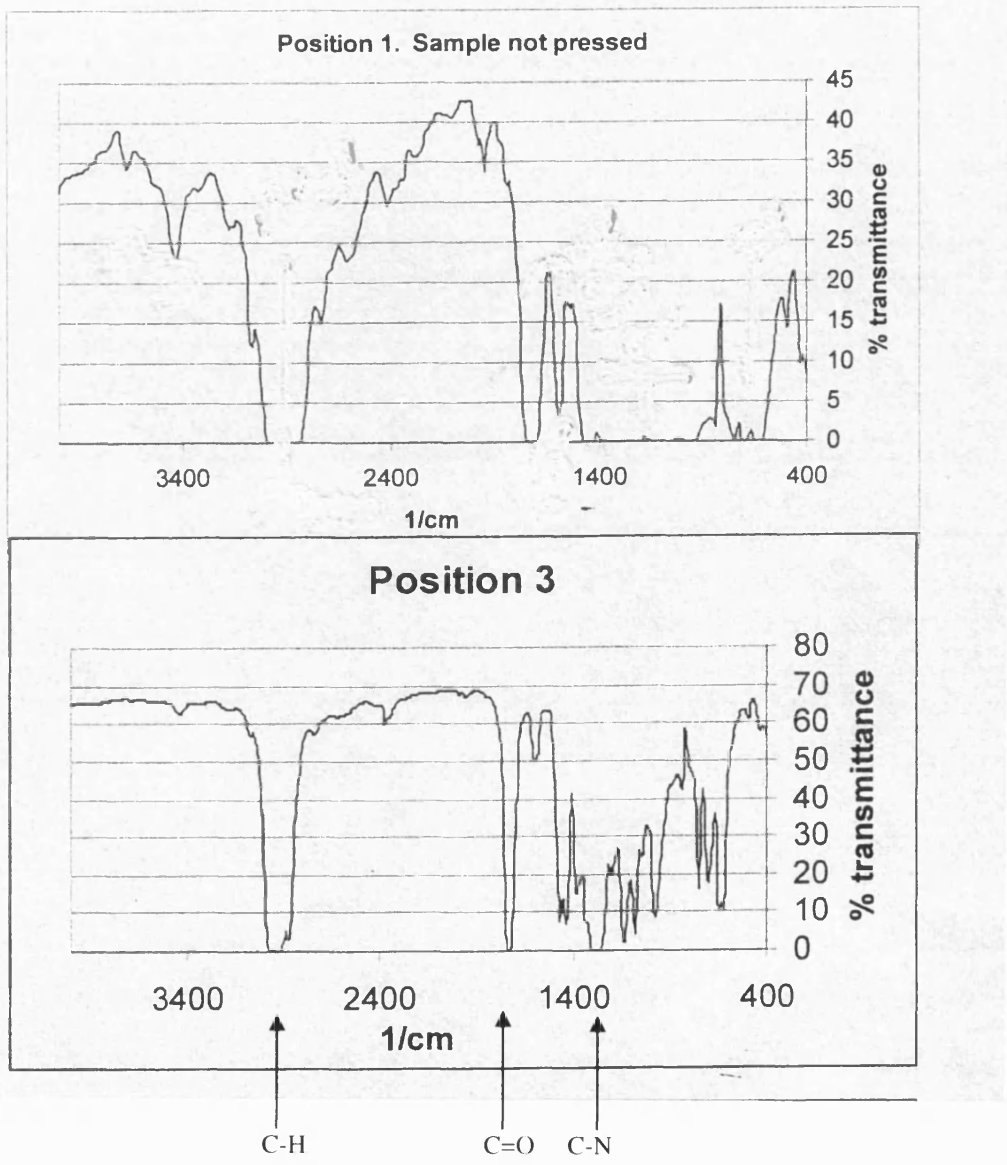
Particle Type		**Al-rich**			**Fe-rich**	**Si-rich**	**Ti-rich**
Representative Spectrum		Al-O	Al-O-Ti-Mg	Al-O-Ti-Mg-C			
3rd Pass	Number	9	31	1	17	7	5
	%	13	44	1			
			59		24	10	7
5th Pass	Number	67	20	1	18	8	6
	%	56	17	1			
			73		15	7	5

4.1.3 Media Volume Reduction

Samples were taken from four positions along an as-new gaiter (see Chapter 3, Figure 3.1m and Table 3.1d), two samples from the sheet polyurethane gaiter film (fabricated into a tapered tube), and two from corrugated sections (one from each of two diameters). Their appearance and texture suggested that either these parts of the gaiter were different grades of polyurethane or they were different as a result of their manufacture. The film samples were soft and pliable, whereas the corrugated samples were harder and more rigid, with a thicker section and showed a shinier surface finish. The corrugated material was also exhibiting a yellowish tinge, which was not seen on the sheet film samples.

The IRS examinations were carried out on a Perkin Elmer Fourier Infra-Red Spectrometer model 1720X. The samples were too thick to be tested 'as-received', not enough radiation was transmitted through the film. The polyurethane film was therefore hot pressed to make them thinner. Samples were scanned in the spectrometer 10 times at a resolution of 4 cm^{-1}. The graphs produced plot transmittance (%) against wavelength (cm^{-1} – multiply by 10^4 to convert to microns for comparison with other literature). IRS examinations suggest through comparison with reference spectra [92, 93], that the PU materials relate to a hexamethylene di-isocyanate and 1:4 butane diol polyurethane (MDI). Since the gaiter spectra show absorbency peaks at 3.00, 3.40, 5.88 and 8.00 microns (or 3333 cm^{-1}, 2900 cm^{-1}, 1700 cm^{-1}, and 1250 cm^{-1}), this probably corresponds to the respective N-H, C-H, C=O and C-N bonds in the polyurethane material [92]. Figure 4.1r shows typical spectrum from an unirradiated sample of gaiter material. It was apparent that all positions on the gaiter were made from the same polyurethane material even though the forming and the manufacturing has been different.

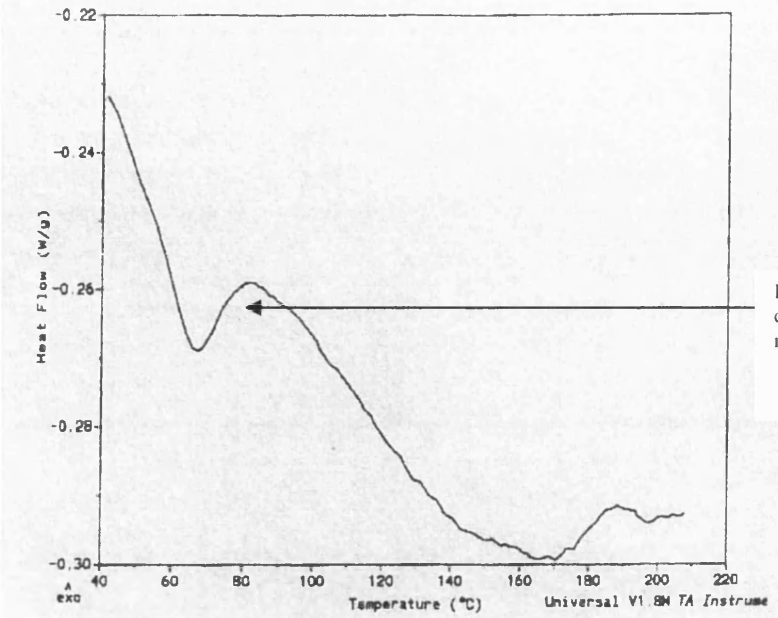
FIGURE 4.1r: TYPICAL INFRA-RED SPECTRUM FOR UNIRRADIATED GAITER POLYURETHANE



The DSC tests were carried out on a TA Instruments machine model No. DSC 2910. The baseline, cell constant and temperature were calibrated using an indium sample in an aluminium pan with nitrogen gas flowing at a rate of 150 cm^3 min^{-1}. The calibrating method used was 'Indium 100 to 200 at 10 °C'. Once the machine was calibrated the polyurethane samples were cut to size and then placed in a sealed aluminium pan with the

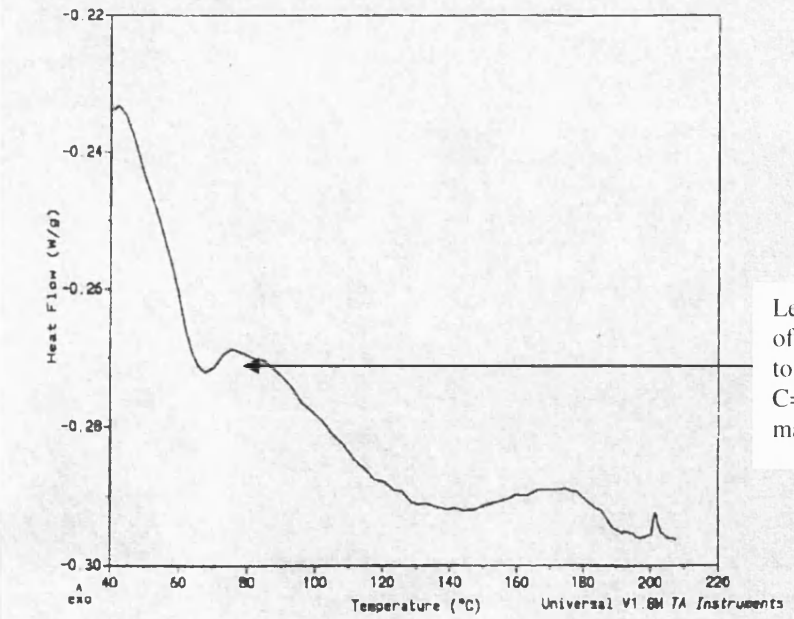
reference sample being an empty aluminium pan. The experimental method used was programmed to go from 30 °C to 210 °C at a ramp rate of 10 °C min^{-1}. DSC graphs again appear similar each sample along the gaiter suggesting that each part of the gaiter is made from the same type of polyurethane. The results show a marked reaction on heating from ~65-70 °C to 100-120 °C, which may be a result of thermal degradation. This could be an enthalpy change or a specific heat change [93]. The literature states that many PU materials thermally degrade liberating oxygen at temperatures up to 120 °C, this is most likely to involve the breakdown of the C-O and C=O bonds [15, 17, 19, 58]. Figure 4.1s shows this reaction from a typical unirradiated sample of gaiter material. It is noticeable that the flexible corrugated parts of the gaiter (at positions 3 and 4) show a less pronounced heat flow reaction than the upper tubular sheet parts (at positions 1 and 2) of the gaiter. This may be due to additional heat input to the polyurethane during the forming of the corrugated section, breaking down some of the C-O/C=O bonds, leaving less bonds available for degradation during these subsequent DSC examinations. If so re-examination of the IRS spectra should show less transmittance at 5.9 and 8.0 microns (1700 and 1250 cm^{-1}). While this does appear to be the case, it is inconclusive due to the difficulties experienced in thinning the polyurethane film. Nevertheless the initial observations of a yellowish tinge in the corrugated part of the gaiter provides compelling evidence that heating had indeed been applied in forming this section.

FIGURE 4.1s: DIFFERENTIAL SCANNING CALORIMETRY GRAPHS FOR AS-NEW POLYURETHANE GAITER MATERIAL



Pronounced heat flow corresponding to the softening range of the polyurethane elastomer

Position 1



Less pronounced heat flow of upper gaiter possibly due to enhanced degradation of C=O/C-O bonds during manufacture

Position 3

The weight loss data is the most pertinent information regarding the physical volume reduction process design in that any major changes may influence whether the use of heat is safe for in-cave. Table 4.1e. shows the results of as-new samples of gaiter polyurethane heated to 110 °C for 21 hours showing weight loss up to 1.34% [93], and as-new sponge media heated to temperatures of 120 °C to 300 °C in 20 °C steps [84]. Again the corrugated part of the gaiter shows different characteristics to the sheet film part of the gaiter. The prior heating undergone by the polyurethane during forming may have made it less stable under subsequent heating, or additions such as plasticisers may have been made to the basic composition. Nevertheless this indicates that the as-new gaiter will release relatively little evolved gas products, and remain relatively stable under an in-cave heat treatment process for volume reduction of waste in the WAHF. The sponge media revealed a similar weight loss up to ~200 °C. As temperatures rise more weight loss is observed, where process temperatures rise above ~220 °C a marked reduction in the thermal stability of the polyurethane media occurs, with the complete breakdown of the polyurethane as the temperatures approach 300 °C. Again like the gaiter materials, the sponge did not melt down under its own weight.

A test rig was set-up using a standard ILW disposal container with thermocouples fitted in each side (see Figure 4.1t) to test the gaiter materials melt down capability under radiant heating (see Figure 3.1k). Commissioning trials were first carried out to measure the heating effect of the system and develop a method of control that will enable the heating trials to be carried out at different soak temperature when applied to polyurethane gaiter and sponge samples. Initially the current was set at 5 amps but the trial had to be aborted since the heat output of the lamps was not raising the liner

TABLE 4.1e: RESULTS OF WEIGHT LOSS ON AS- NEW GAITER AND SPONGE-JET MATERIAL

Sample	Mass before heating (g)	Mass after heating (g)	% Weight loss
Position 1 - 110°C/21h	0.3399	0.3391	0.24
Position 2 - 110°C/21h	0.2360	0.2350	0.42
Position 3 - 110°C/21h	0.2699	0.2667	1.19
Position 4 - 110°C/21h	0.2532	0.2498	1.34
Sponge Media#-120°C	1.5065	1.4781	1.89
140°C	1.6689	1.6387	1.81
160°C	1.6662	1.6365	1.78
180°C	1.4942	1.4775	1.12
200°C	2.1463	2.1174	1.35
220°C	1.3973	1.3701	1.95
240°C	1.9008	1.8460	2.88
260°C	1.4573	1.4123	3.09
280°C	1.8349	1.7825	2.86
300°C	1.9038	1.8467	3.00

Ramp rate 300°C per hour to test temperature, then dwell for 0.3hr [82]. Green media only.

temperature fast enough. Restarting the commissioning using 10 amp saw a steady increase in the liner temperature of ~1.5 to 2 °C min^{-1}. This saw the liner temperature rise to ~100 °C, where liner temperature was maintained at 100 to 102 °C. This setting would be used to raise the temperature within the liner to target soak temperatures of 60 °C, 70 °C, 80 °C, 90 °C, 100 °C, 110 °C, 120 °C and 130 °C, respectively for small samples of polyurethane gaiter. These were tested within open cans inside the disposal liner (see Figure 4.1t.b). Difficulties were encountered with lamp heat control at the desired soak temperatures. Trial 3 saw the amperage turned down to 8 A, but the liner temperature cooled significantly. The trial was repeated to 70 °C but the amperage was only reduced to 9 A. The temperature did not fall, but slowly rose to 73 °C over 5 minutes. For the 80 °C trial a commissioning run was conducted to ascertain the best control point to maintain the target soak temperature. In neither of the previous heating trials did the gaiter samples show any sign of melting. By turning the amperage down to 9.5 A, the target soak temperature appeared to be maintained. This was then repeated using a small gaiter sample in the liner. This did not affect the gaiter material which appeared to have

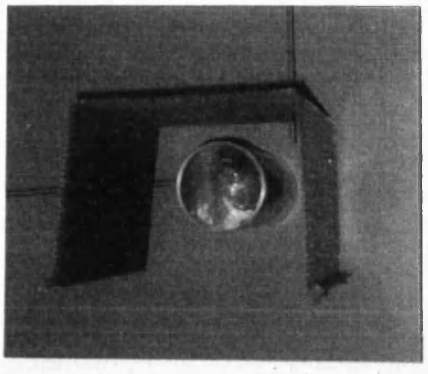
sagged slightly but had certainly not melted. This was repeated at the other target temperature for small samples of both flat film and corrugated gaiter. Some of the corrugated samples appeared to melt down quite well while others appear more reluctant when the temperatures rose above 110 °C. The trials above 100 °C required additional current to gain the necessary heat output from the lamps. The amperage was increased to 11.5 A, 12 A and 12.75 A to increase the liner to 110 °C, 120 °C and 130 °C respectively. The current had to be turned down to 10.5 A, 11.1-11.5 A and 12-12.5 A respectively for each of the target soak temperatures. Trials at 130 °C saw fumes arising from the trial rig and the experiment terminated. The reason was that the corrugated samples were beginning to char rather than melt into a homogeneous mass as originally desired. A subsequent full-scale trial up to 125 °C (Figure 4.1t.c), was a further disappointment in that while the gaiter material softened, it did not melt down under its own self weight. This approach was therefore abandoned for gaiter material.

These trials were also conducted on Sponge-jet media (Figure 4.1t. (c) in centre on plate) and this sponge polyurethane did not melt at all, probably due to the additional cross-linking involved with the toluene di-isocyanate and long chain polyether polyol. Additional thermal stability trials up to 300°C on the sponge media showed no significant weight loss or volume shrinkage on heating [8]

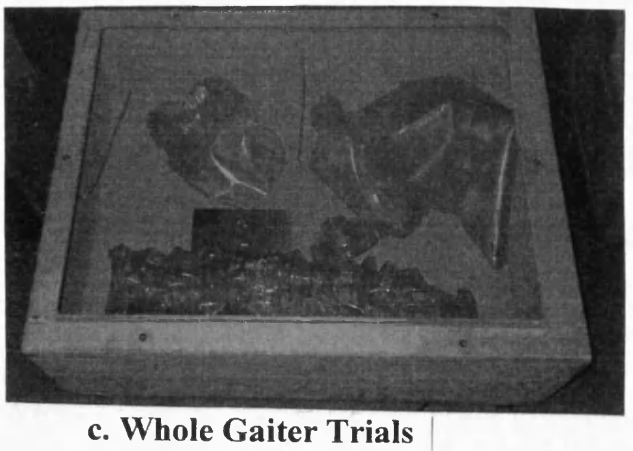
[8] Private communication in September 1998 with Dr T Mays regarding the results of thermal stability analysis on sponge media.

FIGURE 4.1t: FULL SCALE INACTIVE GAITER VOLUME REDUCTION TRIAL

a) Thermocouple Arrangement

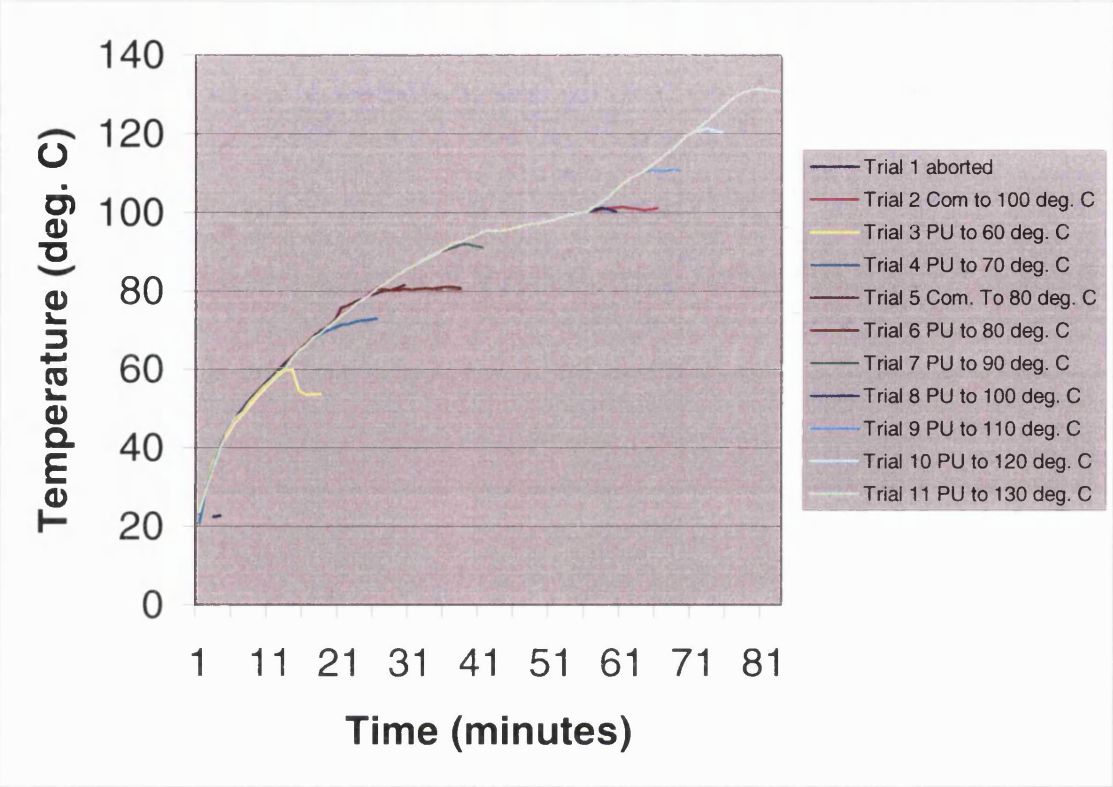


b. Test Sample Trials



c. Whole Gaiter Trials

FIGURE 4.1u: PLOTS OF ILW LINER HEATING TRIALS ON POLYURETHANE GAITER AND SPONGE SAMPLES



The failure of 'free-standing' heat-treatment trials on polyurethane samples has ruled out radiant heating as a method of volume reducing polyurethane materials under their own weight. This has lead to the conclusion that a physical forming process will need to be developed in order to effectively volume reduce the media and gaiter material.

4.2 LOW LEVEL WASTE TRIALS

4.2.1 LLW Trial Sponge Blasting

Trials were carried out using both non-abrasive and abrasive media. A milling machine tool used in cave to machine specimens from radioactive fuel elements required refurbishment and retooling. Due to the complexity of the work this was expected to be a radiation dose intensive operation. It was also expected that using conventional decontamination techniques it would take a long time to get dose rates down to a level that would enable an engineer enough working time within his radiation exposure limit. The options were to either decontaminate and reuse the equipment, or scrap the milling tool and purchase a new machine, and generate more nuclear waste. It was proposed that this was an ideal opportunity to test the non-abrasive Sponge-jet medium capability in the cave roof enclosure area.

The abrasive trials initially involved a stripping trial using girder sections, while the main radioactive active trial would involve using the contaminated steel cylinders. The active trial will involve monitoring and sampling to be carried out on the first steel cylinder (PRDO Station) as described in Chapter 3.2. This initially involved evaluating the radioactivity inventory of a relatively small trial area in order to undertake a controlled assessment before continuing with the process of decontaminating the whole cylinder and following cylinders. This would also ensure that the work meets with the principle of ALARP/ALARA, as described in Chapter 2.

Abrasive Paint Stripping Trial

The WAHF 15 ton overhead gantry crane was replaced rendering the old crane parts as a large volume of LLW. The crane was originally fabricated and painted offsite in a non-active environment. It was installed prior to radioactive operations in the WAHF. There has been no history of contamination involving the crane structure, and the cut up parts appear to be radioactively clean following a monitoring survey. Unfortunately the steel work can not be released for non- radioactive disposal (known as free release) because the heavily painted and corroded areas may contain shielded contamination that could exceed the regulatory limits. The trial will aim to clean the steel down to base metal in order to facilitate a more thorough monitoring survey, lending greater confidence that the material is 'clean'. Furthermore it will establish whether this sort of material can be stripped economically in as far as the benefits out weigh the costs.

Using the Silver abrasive medium at maximum blasting conditions the two girder sections described in Chapter 3.2 were cleaned down to bare metal. The work took two days and three process workers, hence 6 man operating days. This included girder loading and unloading to/from the enclosure, dressing, blasting, monitoring, collection and recycling operations. It has been assumed that this could easily be reduced to 4 man operating days when the process is improved for routine operation. For example automated collection and separation of the medium for recycling. The key parameters being considered during the assessment of this trial are as follows:

Initial girder LLW spatial volume	0.66 m^3
Potential packing optimisation	0.11 m^3
Bulk density of the medium	530 kg m^{-3}
Total continuous processing time	2 full days

Total operator processing time	6 (4) work days
Assumed daily tariff	£200 man day^{-1}
Spent LLW medium mass	~140 kg (6 x 23kg bags)
volume	~0.26 m^3
Potential medium volume reduction ratio	3:1
Final medium waste volume	~0.086 m^3
Assumed LLW disposal rate	£3000 m^{-3}
Cost of new medium	£3.05 kg^{-1}

Note: costs estimated in 1998.

The girder sections would incur Drigg disposal costs estimated to be in the region of ~£2k (£3000 m^{-3} x 0.66 m^3), based on the bare volume the waste would occupy. The girders themselves would occupy a space of approximately 0.66 m^3, this could be reduced by judicious packing, where the volume of these particular girders could be reduced by nearly 17% (see Figure 3.2c). There are real economies of scale that would be gained when packing these items with other similar material within a large ISO freight. It is difficult to assess these benefits so the trial has been based simply on the volume the two girders within their best packing arrangement i.e ~0.55 m^3.

The additional costs involved in decontaminating or stripping paint from the girders to confirm or ensure FR levels have been achieved, fall in to three categories: BNFL disposal charges for spent medium, process labour charges and materials costs. No account has been made of capital plant cost and depreciation. The costs are as follows:

Spent Medium Disposal	£3k m^{-3} x 0.086 m^3 = £258
Manpower	£200 day^{-1} x 4 days = £800

Medium purchase	£3.05 kg^{-1} x 140 kg	= £427
	Total Costs	= £1485

There is a benefit from the scrap metal such as scrap costs of between £38 and £46 per ton. The real cost savings are replacement costs for such material (girders) as stock for new gantry cranes, which will be substantially higher. This aspect has not been evaluated further during this trial. So the cost of cleaning a 0.55 m^3 volume (surface area of ~8.63 m^2) of LLW by stripping paint with the Sponge-jet process costs ~£1443. The cost of LLW disposal of the same volume is £1650 (£3000 m^{-3} x 0.55 m^3). This suggests that using Sponge-jet a saving of just over £200 could be achieved by stripping paint from these specific items of waste, such that they may be disposed as free release for reuse, rather than as LLW. If this form of waste was stripped routinely in order to ensure unhindered monitoring and very low activity levels are confirmed, cost benefits of at least £364 m^{-3} (200 x 1/0.55) are possible. This suggests a saving of just over 12% could be achieved on waste disposal costs, depending on the ratio of surface area cleaned, to LLW volume saved. Even though there are a number of uncertainties (e.g. thickness and type of paint) that could reduce this value it is unlikely to challenge the viability of this process for this type of waste form. If there are large amounts of waste with similar volume to surface area: LLW volume ratio the cost – benefit is unequivocally worthwhile as long as the installed plant can be offset against enough waste processing. It should also be remembered that these calculations are using the trial labour cost and any improved process for routine operation should reduce these costs dramatically.

Active LLW Trial on Steel Cylinders

The PRDO stations were monitored with a beta-gamma (BP3 and DP2) probe to gain a measure of the activity and radiation levels in the trial area in counts per minute or second

(c.p.m or s.). Samples of the contamination are taken using paper swab wipes which capture a proportion of loose surface contamination, and they are then put into a Scaler (sodium iodide detector) (see Chapter 2) to measure the radioactivity held on the swab (again in c.p.m. or s). Figure 4.2a summarises the initial surveys of the first PRDO station prior to cleaning with the Sponge-jet.

These measures of radioactivity in c.p.s. are then converted to an equivalent radioactivity in becquerels (Bq) per square centimetre using a surface contamination 'ready-reckoner' that has been derived from the standard fingerprint for the accepted mix of radionuclides found in WAHF contaminants. This conversion is described in Section 2.3. The total radioactivity inventory for the trial area is therefore estimated depending on the area of contamination. The results of this trial are presented in the following section.

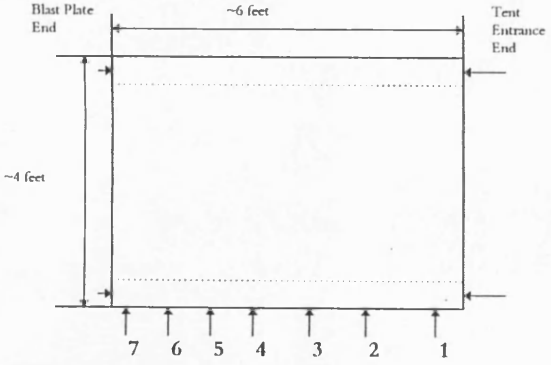
The trial area of the PRDO station was an area of the inside of one end of the cylinder up to 0.3 m from the end face, plus the complete surface of one end. This came to a total area of 1.51 m^2. The mean activity for this area prior to cleaning was based on the survey in Figure 4.2a where the activity on the internal surfaces was up to 200c.p.s., and the end faces contained loose contamination up to 80 c.p.s. and loose + fixed contamination up to 5000 c.p.s. $\beta\gamma$. The mean radioactivity for these areas for the purposes of this experiment was assumed, cautiously, to be 150 c.p.s. on the inside area, and an average of both the loose swab and loose + fixed probe measurements, at 818 c.p.s.. Based on the geometry of the DP2 probe and its efficiency approximately 35 c.p.s. is actually 4 c.p.s. cm^{-2}. The total activity inventory of the controlled area is therefore approximately 0.7 MBq.

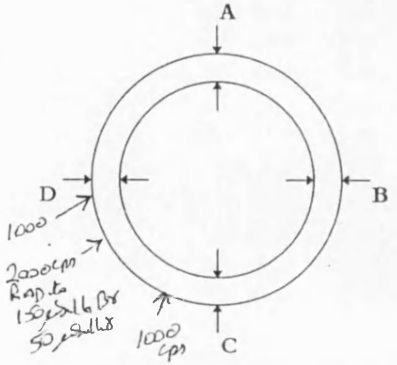
FIGURE 4.2.a: SUMMARY OF INITIAL HEALTH PHYSICS MONITORING SURVEYS FOR THE FIRST PRDO FLASK POSTING STATION PRIOR TO DECONTAMINATION WITH SPONGE-JET

PRDO STATION Id (Eg. First/Second/Third): No1
Survey Report Stage: Pre. OPS
(Eg. Pre-Ops, After Green, After Silver etc)

Areas inside PRDO to 200 cps BKP
BSE To 5Kcps BK
RAD to 350 µSv/h BK
40 µSv/h K

FIXED MONITORING POINTS





Monitoring by swab and RO2 at points A to D inside and outside the station at 6 to 7 equi-spaced points along the station.

Both the Tent Entrance End (TEE) and the Blast Plate End (BPE) to be monitored at points A to D.

Generally survey the whole station and Id. and swab areas higher than the general levels at the fixed points.

MEASUREMENTS BY SWAB/RO2: Activity in cps/swab ○ Probe Reading

POSITION units:	1	2	3	4	5	6	7	TEE	BPE	High Spot Position/Swab/Radiation	Comments
A (0 degrees)	15	10	7	6cps	7	7	10	10	20	(50)	Swabs Radiation < Background
B (90 degrees)	7	7	4	8	8	7	7	80	30	(1000)	N.B BACKGROUND 10µSv/h BK+K
C (180 degrees)	7	5	10	6	6	4	7	20	20	(5K) BPE 350µSv/h BK 40µSv/h K BSE	
D (270 degrees)	10	5	8	7	6	10	6	30	30	(2000) TEE 150µSv/h BK 50µSv/h K TEE	

Following a single blasting pass across this area the PRDO station was resurveyed over the control area. The results of this survey are presented in Figure 4.2b. From this it was clear that very little loose contamination remained (<5c.p.s.), while the DP2 probe detected contamination levels generally around 100 c.p.s. for the whole area, with the exception of one high spot between 200 and 500 c.p.s.. The high spot corresponded to the high areas from before the trial. The assumed measure of residual activity for the inner area of the cylinder was the probe measurement of 100 c.p.s., while a mean value of 121 c.p.s. is used for the end face to accommodate the high spot. The high spot occupying approximately $1/12^{th}$ of the circumference of the end face area. This gives rise to a total activity inventory of approximately 0.2 MBq.

Therefore the estimated activity removed by one pass of Silver Sponge-jet medium is approximately 0.5 MBq. This is summarised by the following calculation.

Contamination Transfer Summary

Control Area

One End - $\frac{\pi D^2}{4} - \frac{\pi d^2}{4}$ = Area of End Face (m^2)

$1.37 - 0.82 = 0.55\ m^2$

Inner Surface - πd x length of cyl.cleaned = Area of Inner Face (m^2)

$3.20 \times 0.3 = 0.96\ m^2$

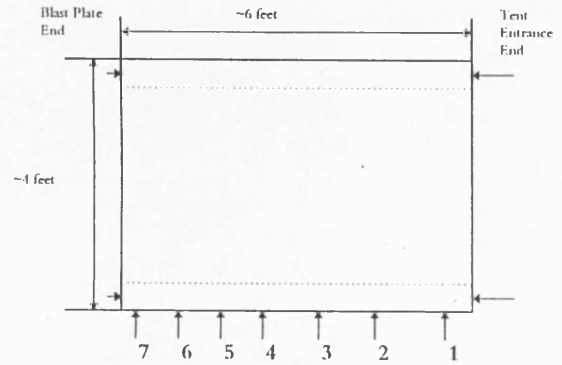
Total Control Area = $1.51\ m^2$

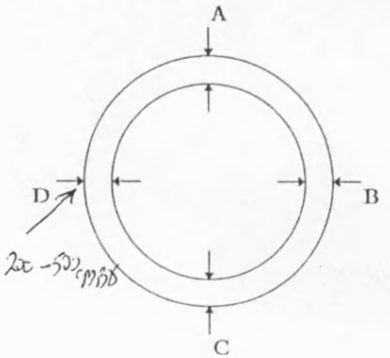
FIGURE 4.2.b: SUMMARY OF HEALTH PHYSICS MONITORING SURVEYS FOR THE CONTROL AREA ON THE FIRST PRDO FLASK POSTING STATION AFTER ONE DECONTAMINATION PASS WITH SPONGE-JET

Base Plate and Wall <5cps βθ Stand
TEE WALL <5cps
B Side Wall 9cps βθ
D Side Wall <5cps.
(ENCLOSURE WALL)

PRDO STATION Id (Eg. First/Second/Third): 1
Survey Report Stage: AFTER SILVER TEE. END ONLY
(Eg. Pre-Ops, After Green, After Silver etc)

FIXED MONITORING POINTS





Monitoring by swab and RO2 at points A to D inside and outside the station at 6 to 7 equi-spaced points along the station.

Both the Tent Entrance End (TEE) and the Blast Plate End (BPE) to be monitored at points A to D.

Generally survey the whole station and Id. and swab areas higher than the general levels at the fixed points.

MEASUREMENTS BY SWAB/~~RO2~~: DP2 approx 100cps DP2 Internal & External.

POSITION units:	1	2	3	4	5	6	7	TEE	BPE	High Spot Position/Swab/Radiation	Comments
A (0 degrees)	<5	<5	<5					<5			Air Samples
B (90 degrees)	<5	<5	<5					<5			run for 30 mins
C (180 degrees)	<5	<5	<5					<5			initial count: 39cpm α, 5787cpm β,
D (270 degrees)	<5	<5	<5					<5			after 24hr decay: 28 cpm α 5120 cpm β.

2cps (69cpm) by Scaler.

TEE 200-500 cps βθ Probe.

Active Inventory of Contaminated Control Area

Based on DP2 Probe measurements of 815 cps on end and 150 cps on inner surface;

Average Value

$$\text{Activity} = \frac{815}{35}(4 \times 0.55 \times 10^4) + \frac{150}{35}(4 \times 0.96 \times 10^4)(\text{Bq})$$

$$= 5.1 \times 10^5 + 1.6 \times 10^5\ (\text{Bq})$$

$$= \underline{6.7 \times 10^5\ \text{Bq}}$$

where the DP2 probe efficiency means ~35 c.p.s. is equivalent to ~4 Bq cm^{-2}.

Post Trial Active Inventory on Control Area

Based on DP2 Probe Measurements Surveyed Over Control Area;

Average Value

$$\text{Activity} = \frac{121}{35}(4 \times 0.55 \times 10^4) + \frac{100}{35}(4 \times 0.96 \times 10^4)(\text{Bq})$$

$$= 7.6\text{E}04 + 1.1 \times 10^5\ (\text{Bq})$$

$$= \underline{1.9 \times 10^5\ \text{Bq}}$$ (where DP2 probe efficiency mean ~35 c.p.s. is equivalent to ~4 Bq cm^{-2}).

$$\text{Decontam. Factor(DF)} = \frac{6.7 \times 10^5}{1.9 \times 10^5}$$

$$= \underline{3.5}$$ (for the first pass only)

Estimated Activity Removed During Trial

Mean Value

$$\text{Activity} = 6.7 \times 10^5 - 1.9 \times 10^5\ (\text{Bq})$$

$$= \underline{\sim 4.8 \times 10^5\ \text{Bq}}$$

This data suggests the Sponge-jet process using Silver abrasive medium to remove the fixed contamination is capable of achieving a decontamination factor of ~3.5 in one pass.

Throughout the blasting period of 30 minutes the atmosphere of the enclosure was sampled using a β-in–air sampler, which takes air at a rate of 2.2 m^3 hr^{-1}. The air is passed through a filter and any radioactive contamination particles are collected on the filter paper. The paper is measured in the Scalar instrument soon after the trial and again after 24 hours to take account of any radon that may also have been collected. The radioactivity collected during the control area trial was 5120 c.p.m. β (~85 c.p.s.), see Figure 4.2b. This represents ~2.75 DAC's (Derived Air Counts) and ~1.37 DAC Hr for β. This level of operational airborne contamination is not considered to be a safety problem for operators in respiratory protection.

The total airborne activity can be calculated by taking account of the sampling rate, duration of sampling, sampler efficiency, enclosure air volume, blasting air volume rate and duration. The average airborne activity is estimated to be ~320 Bq m^{-3}, while the enclosure volume is approximately 31.2 m^3 and the blasting volume based on a maximum blast rate (4.1 m^3 min^{-1}) and a 1/2hr blast time, is 123 m^3. This calculation can be summarised as follows;

Estimation of Airborne Activity Generated During Trial

Blasting Period	30 minutes
Activity Collected on β in Air Filter	5120 c.p.m.
Air Sampling Rate	2.2 m^3 hr^{-1}
Derived Air Count (DAC) for β	7000 c.p.m.
Scaler Efficiency	24%

$$\text{Average Airborne Activity} = \frac{(\text{c.p.m.}/60) \times 100}{2.22 \times 0.5 \times 24} \ (\text{Bq m}^{-3})$$

$$= \underline{320 \text{ Bq m}^{-3}}$$

Tot. Air Generated in Trial
= (one enclosure volume)
+ (blast rate x duration) (m^3)

= (4 x 3.25 x 2.4) + (4.1 x 30) (m^3)

= $\underline{154.2\ m^3}$

Therefore Total Airborne Activity Generated = $\underline{4.9 \times 10^4\ Bq}$

The total airborne activity generated is approximately 0.05 MBq, so the release fraction as a proportion of the original activity inventory on the control area is:

$$\text{Release Fraction } (RF_{pre}) = \frac{4.9 \times 10^4}{6.7 \times 10^5}$$

$$= \underline{0.07}$$

As a proportion of the activity removed from the control area the release fraction is:

$$\text{Release Fraction } (RF_{post}) = \frac{4.9 \times 10^4}{4.8 \times 10^5}$$

$$= \underline{0.102}$$

This appears consistent with the supplier's claim of up to 94% less airborne dust than with conventional blasting techniques.

The medium used in the first trial was collected and monitored; Figure 4.2c gives summary data on the monitoring results for the reusable and spent medium. Taking the medium as a whole the mean activity per 25 cm^3 sample measured on the scaler is ~377 c.p.m. β. By taking account of the volume of medium used and the scaler efficiency, an estimation of the activity transferred to the medium as a whole can be made as follows:

Estimation of Activity in Spent Medium

Mass of Medium Used (Four Boxes at 23kg/box)	92 kg
Bulk Density of Medium (at 33.3lb/c.ft.)	533.4 kg m^3
Mass of Medium Used (One Pass Only)	0.173 m^3
Monitored Sample Size	~25 cm^3
Monitored Values on Medium (by Scaler)	Mean- 377 c.p.m. β
	Max.-750 c.p.m. β
Scaler Efficiency	30%

Activity in Medium is therefore;

Average Value

$$\text{Activity} = \frac{(\text{c.p.m./60})}{0.3} \times \frac{0.173 \times 10^6}{25} \text{ (Bq)}$$

$$= 1.4 \times 10^5 \text{ Bq}$$

Maximum Value

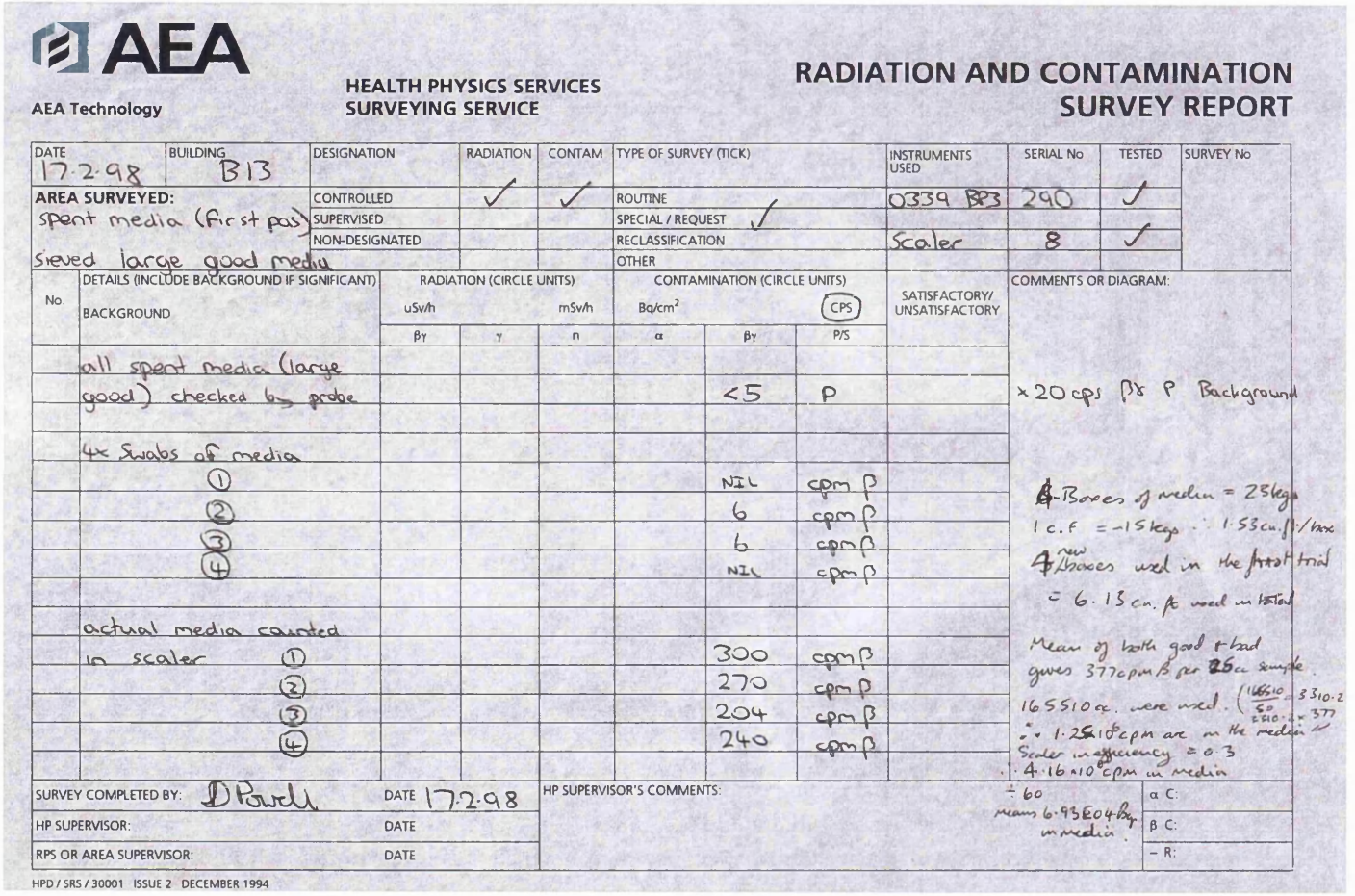
$$\text{Activity} = 2.9 \times 10^5 \text{ Bq}$$

So the activity contained in the medium could be as much as ~0.3 MBq (60% of the amount estimated to have been removed). Since the medium retains contamination within its matrix (see Chapter 4.1) and much contamination may not be favourably orientated toward the Scalar detector, there is a potential for the medium to provide a degree of shielding, and so estimates of contamination may be underestimated. It is therefore likely that the true medium value is well above the mean value.

Another contamination transfer route will be to the walls, floor and ceiling of the enclosure, from airborne contamination settling, falling off medium particles as they rebound/ricochet around the enclosure following impact with the PRDO station, and during hovering operations to collect the medium for recycling. The walls, floor and ceiling of the enclosure were swabbed following collection of the Silver medium used with the control area trial. All swabs were found to be <5 c.p.s. β. While this is a low value the

FIGURE 4.2c: HEALTH PHYSICS SURVEY REPORTS FOR THE SILVER MEDIum USED DURING THE CONTROL AREA DECONTAMINATION TRIALS

Reusable Medium



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HEALTH PHYSICS SERVICES
SURVEYING SERVICE

RADIATION AND CONTAMINATION
SURVEY REPORT

DATE	BUILDING	DESIGNATION	RADIATION	CONTAM	TYPE OF SURVEY (TICK)	INSTRUMENTS USED	SERIAL No	TESTED	SURVEY No
17·2·98	B13	CONTROLLED	✓	✓	ROUTINE	0339 BP3	290	✓	
AREA SURVEYED: spent media (first pass)		SUPERVISED			SPECIAL / REQUEST ✓				
		NON-DESIGNATED			RECLASSIFICATION	Scaler	8	✓	
sieved large good media					OTHER				

No.	DETAILS (INCLUDE BACKGROUND IF SIGNIFICANT)	RADIATION (CIRCLE UNITS) uSv/h βγ	RADIATION (CIRCLE UNITS) uSv/h γ	RADIATION (CIRCLE UNITS) mSv/h n	CONTAMINATION (CIRCLE UNITS) Bq/cm² α	CONTAMINATION (CIRCLE UNITS) Bq/cm² βγ	CONTAMINATION (CIRCLE UNITS) (CPS) P/S	SATISFACTORY/ UNSATISFACTORY	COMMENTS OR DIAGRAM:
	BACKGROUND								
	all spent media (large good) checked by probe					<5	P		×20 cps βγ P Background
	4× Swabs of media								
	①					NIL	cpm β		4 Boxes of media = 25kgs
	②					6	cpm β		1 c.f = 15kgs ∴ 1·53cu.ft/box
	③					6	cpm β		4 new boxes used in the first trial
	④					NIL	cpm β		= 6·13 cu. ft used in total
	actual media counted								
	in scaler ①					300	cpm β		Mean of both good + bad gives 377 cpm β per 25cc sample.
	②					270	cpm β		165510 cc were used. (165510/50 = 3310·2 ; 3310·2 × 377
	③					204	cpm β		= 1·25×10⁶ cpm are in the media
	④					240	cpm β		Scaler inefficiency = 0·3
									∴ 4·16×10⁶ cpm in media

SURVEY COMPLETED BY: D Powell	DATE 17·2·98	HP SUPERVISOR'S COMMENTS:	÷60 means 6·93E04 Bq in media.	α C:
HP SUPERVISOR:	DATE			β C:
RPS OR AREA SUPERVISOR:	DATE			– R:

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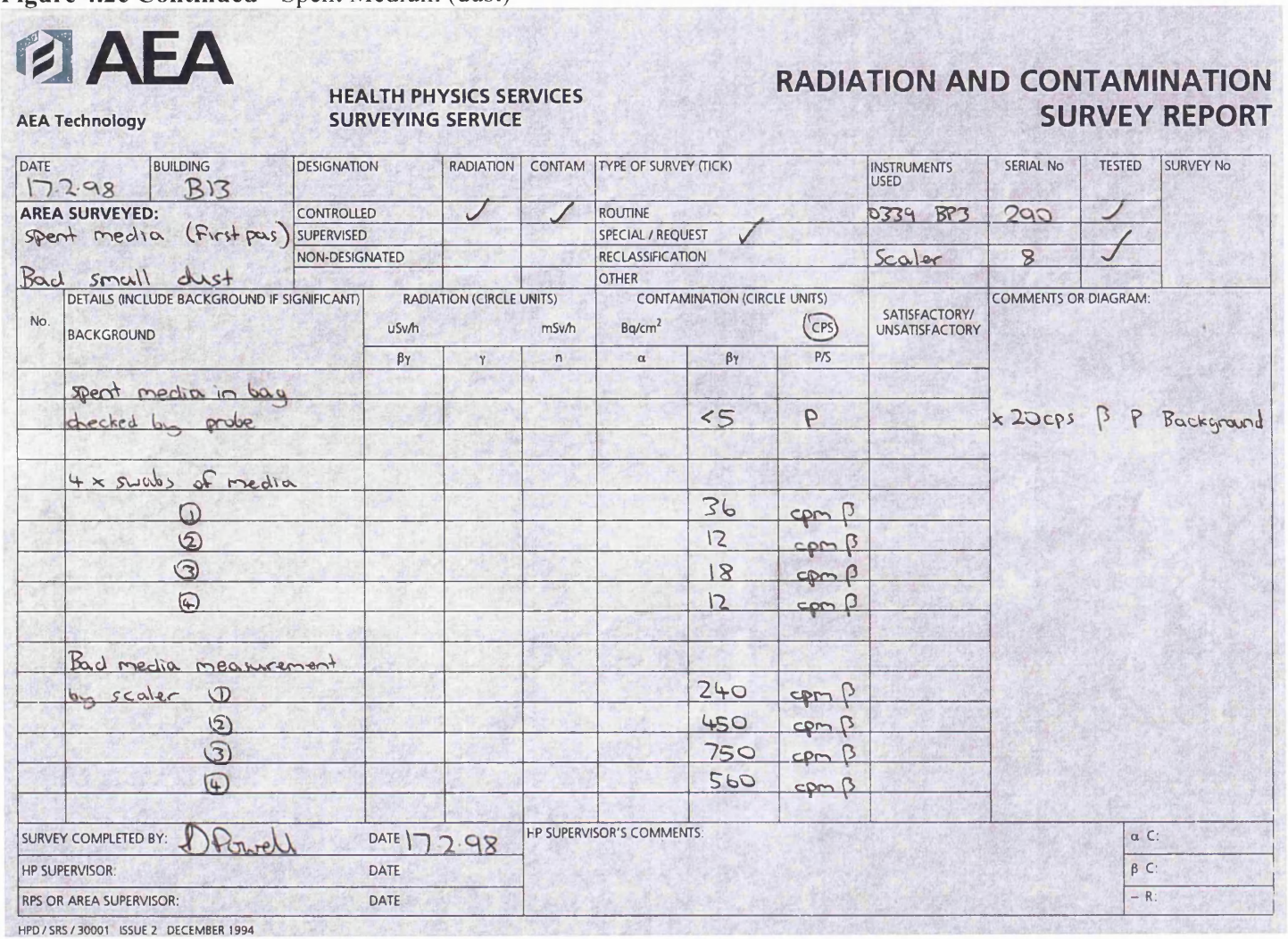
Figure 4.2c Continued - Spent Medium (dust)



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HEALTH PHYSICS SERVICES
SURVEYING SERVICE

RADIATION AND CONTAMINATION
SURVEY REPORT

DATE	BUILDING	DESIGNATION	RADIATION	CONTAM	TYPE OF SURVEY (TICK)	INSTRUMENTS USED	SERIAL No	TESTED	SURVEY No
17.2.98	B13								
AREA SURVEYED:		CONTROLLED	✓	✓	ROUTINE	0339 BP3	290	✓	
spent media (first pas)		SUPERVISED			SPECIAL / REQUEST ✓				
		NON-DESIGNATED			RECLASSIFICATION	Scaler	8	✓	
Bad small dust					OTHER				

No.	DETAILS (INCLUDE BACKGROUND IF SIGNIFICANT)	RADIATION (CIRCLE UNITS) uSv/h βγ	RADIATION (CIRCLE UNITS) mSv/h γ	RADIATION (CIRCLE UNITS) mSv/h n	CONTAMINATION (CIRCLE UNITS) Bq/cm² α	CONTAMINATION (CIRCLE UNITS) Bq/cm² βγ	CONTAMINATION (CIRCLE UNITS) (CPS) P/S	SATISFACTORY/ UNSATISFACTORY	COMMENTS OR DIAGRAM:
	BACKGROUND								
	spent media in bag								
	checked by probe					<5	P		x 20cps β P Background
	4 x swabs of media								
	①					36	cpm β		
	②					12	cpm β		
	③					18	cpm β		
	④					12	cpm β		
	Bad media measurement								
	by scaler ①					240	cpm β		
	②					450	cpm β		
	③					750	cpm β		
	④					560	cpm β		

SURVEY COMPLETED BY: DPowell	DATE 17.2.98	HP SUPERVISOR'S COMMENTS:	α C:
HP SUPERVISOR:	DATE		β C:
RPS OR AREA SUPERVISOR:	DATE		– R:

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inner enclosure surface area is ~61 m^2. The estimated residual contamination activity on the inside of the enclosure can be calculated as follows:

Estimation of Other Contamination Transfers

Swabs of the enclosure walls after the initial trial	<5 c.p.s. β
Enclosure inner surface area (4m x 3.25m x 2.4m)	~60.8 m^2

Average Value

$$\text{Activity} = \frac{2.5}{35}(4 \times 60.8 \times 10^4)$$

$$= 1.7 \times 10^5 \text{ Bq}$$

So the residual activity on the inside surfaces of the enclosure are just under 0.2 MBq. The results of the control area trial can be summarised as follows:

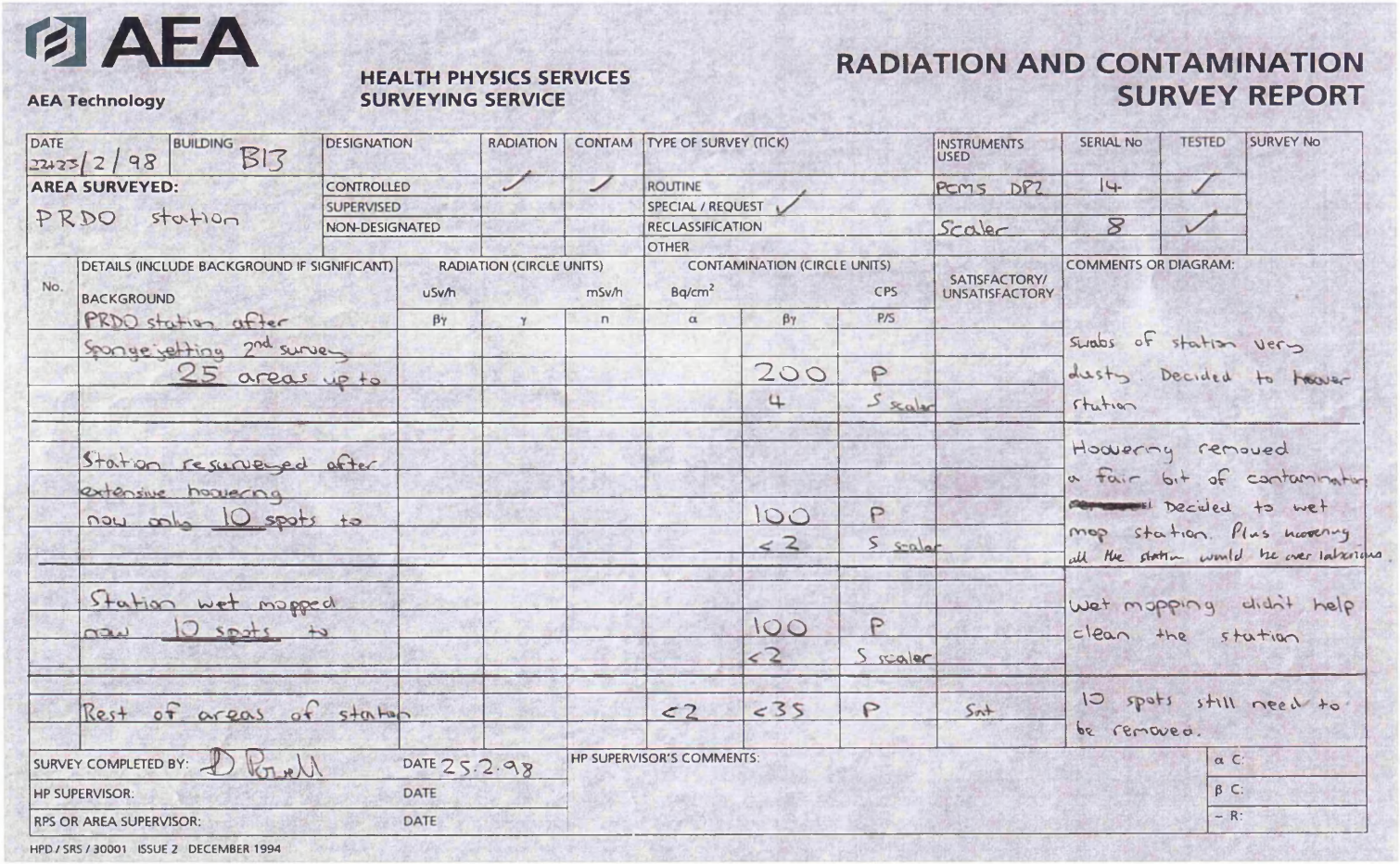
Pre-Ops. Activity on Control Area	6.7×10^5 Bq
Post-Ops. Activity on Control Area	1.9×10^5 Bq
Decontamination Factor (DF)	~3.5
Activity Removed	4.8×10^5 Bq (~72%)
Airborne Activity	4.9×10^4 Bq
	(~10.2% of that removed)
Release Fraction(RF_{pre})	~0.07
(RF_{post})	~0.102
Medium Activity	~1.4×10^5 Bq (mean)
	~2.9×10^5 Bq (Max.)
	(~30-60% of that removed)
Residual Surface Collection	1.7×10^5 Bq
	(~35% of that removed)

Clearly there are substantial errors bounds in the activity measurements, but nevertheless it would appear that the majority of the radioactivity removed from the controlled area could be accounted for in these estimates of the radioactive contamination transfer balance.

The stations are cast steel cylinders ~1.32 m in diameter (O/D) and ~1.83 m long with a ~0.15 m wall thickness. This relates to ~14.55 m^2 of surface area to be decontaminated on each PRDO station. The outer surfaces were painted and the inner surfaces machined with varying degrees of corrosion. The ends were the most contaminated areas and had the worst corrosion, and following the control area trial the whole cylinder was blast clean all over. Blasting operations continued on the PRDO station until it was it very difficult to detect activity above the relatively high background levels of the cave roof area. Figure 4.2d summarises Health Physics surveys of the cylinder after the second pass, and describes attempts to remove the remaining high spots of contamination.

After the second session of blasting the PRDO station was reduced to 25 identifiable patches of elevated contamination up to 200 c.p.s. by DP2 probe. While the surface of the cylinder was very dusty the swabs only collected up to 4 c.p.s. by Scalar. The surface was 'hoovered' to remove the dust and subsequently only 10 spots up to 100 c.p.s. by DP2 probe. Loose contamination was now down to <2 c.p.s. by Scalar. Wet mopping did not clean the cylinder any further so the remaining contamination was activity that was

FIGURE 4.2d: FURTHER HEALTH PHYSICS MONITORING SURVEYS OF THE PRDO STATION CYLINDERS



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HEALTH PHYSICS SERVICES
SURVEYING SERVICE

RADIATION AND CONTAMINATION
SURVEY REPORT

DATE	BUILDING	DESIGNATION	RADIATION	CONTAM	TYPE OF SURVEY (TICK)	INSTRUMENTS USED	SERIAL No	TESTED	SURVEY No
22/23/2/98	B13	CONTROLLED	✓	✓	ROUTINE	Pcms DP2	14	✓	
AREA SURVEYED: PRDO station		SUPERVISED			SPECIAL / REQUEST ✓				
		NON-DESIGNATED			RECLASSIFICATION	Scaler	8	✓	
					OTHER				

No.	DETAILS (INCLUDE BACKGROUND IF SIGNIFICANT)	RADIATION (CIRCLE UNITS) uSv/h βγ	γ	mSv/h n	CONTAMINATION (CIRCLE UNITS) Bq/cm² α	βγ	CPS P/S	SATISFACTORY/ UNSATISFACTORY	COMMENTS OR DIAGRAM:
	BACKGROUND PRDO station after								
	Sponge jetting 2nd survey								Swabs of station very
	25 areas up to					200	P		dusty. Decided to hoover
						4	S scaler		station
	Station resurveyed after								Hoovering removed
	extensive hoovering								a fair bit of contamination
	now only 10 spots to					100	P		[redacted] decided to wet
						<3	S scaler		mop station. Plus hoovering
									all the station would be over laborious.
	Station wet mopped								Wet mopping didn't help
	now 10 spots to					100	P		clean the station
						<3	S scaler		
	Rest of areas of station				<2	<35	P	Sat	10 spots still need to
									be removed.

SURVEY COMPLETED BY: D Rowell	DATE 25.2.98	HP SUPERVISOR'S COMMENTS:	α C:
HP SUPERVISOR:	DATE		β C:
RPS OR AREA SUPERVISOR:	DATE		– R:

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Survey following second pass

Figure 4.2d Continued - Treatment of high spots

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Radiation & Contamination Survey Report
Health Physics Services

Date:	Building:	Designation	Radiation	Contam.	Type of Survey (tick)	Instruments used	Serial No.	Tested	Survey No.
26.2.98	B13	Controlled	✓	✓	Routine	Minicon	6	X	
Area Surveyed: Decontam opps on PRDO station		Supervised			Special/Request ✓				
		Non-designated			Reclassification				
					Other				

No.	Details (include background if significant) Background	Radiation (circle units) µSv/h βγ	γ	mSv/h n	Contamination (circle units) Bq/cm² α	CPS βγ	P/S	U/S S or K	Start Time	Comments or Diagram:
	6 x Spots inside Station to 80 cps βδ P minicon									
	attempts to remove by grinding 2x spots					<20	P			
	4 x Spots still to do					40	P		*	Grinding removes contam but only slowly *
	attempt to spongejet area to 100 cps βδ P minicon all areas attempted to clean now					<20	P			* Spongejetting removed contamination *
*	PRDO station after further spongejetting awaiting final? survey									

Survey completed by: J D Powell	Date 26.2.98	HP Supervisor's Comments:	α C:
HP Supervisor:	Date		β C:
RPS or Area Supervisor:	Date		– R:

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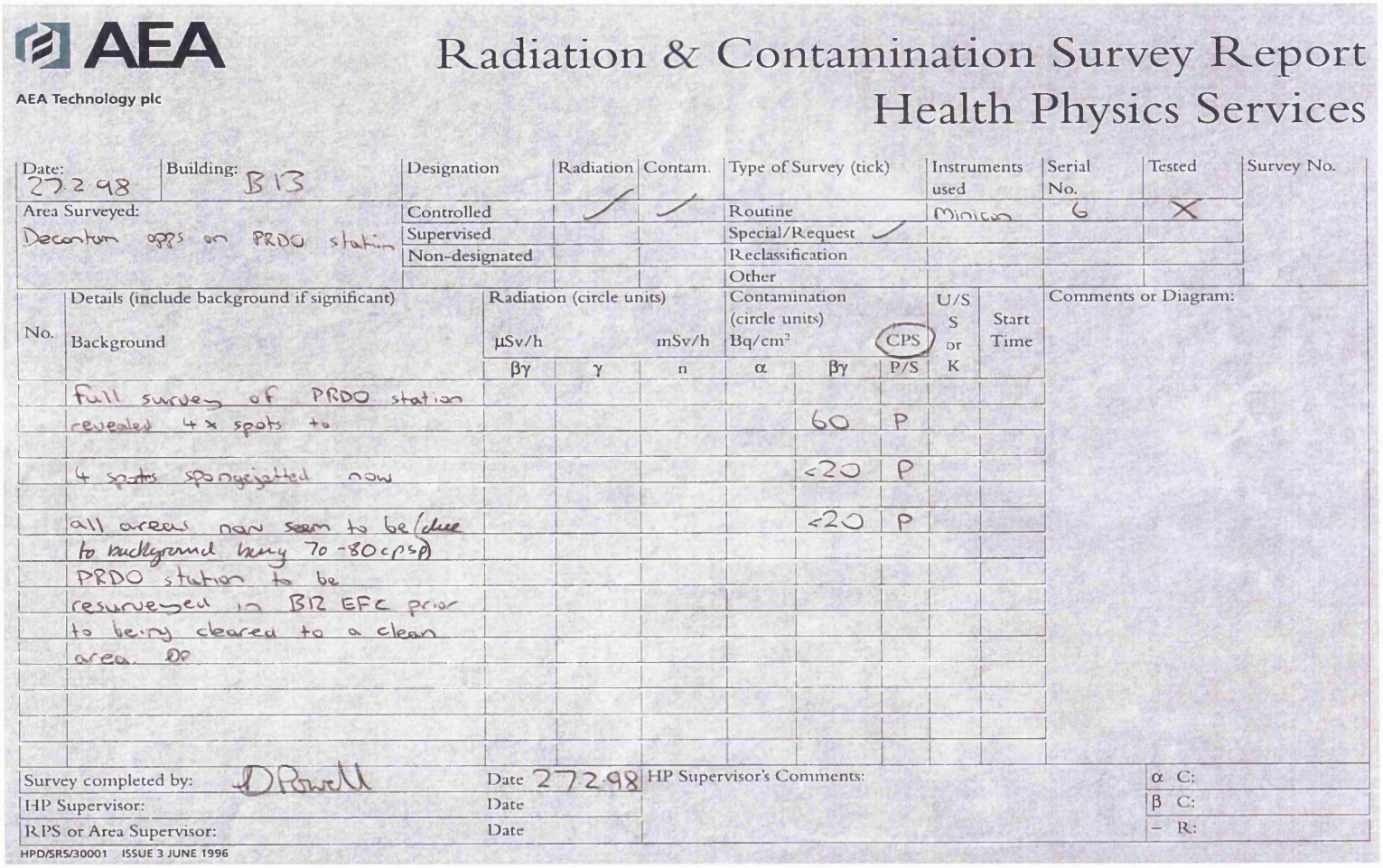
Figure 4.2d Continued - Final measurements before move to low background area



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Radiation & Contamination Survey Report
Health Physics Services

Date:	Building:	Designation	Radiation	Contam.	Type of Survey (tick)	Instruments used	Serial No.	Tested	Survey No.
27 2 98	B13	Controlled	✓	✓	Routine	Minicon	6	X	
Area Surveyed:		Supervised			Special/Request ✓				
Decontam opps on PRDO station		Non-designated			Reclassification				
					Other				

No.	Details (include background if significant) Background	Radiation (circle units) µSv/h βγ	γ	mSv/h n	Contamination (circle units) Bq/cm² α	βγ	CPS P/S	U/S S or K	Start Time	Comments or Diagram:
	full survey of PRDO station									
	revealed 4 x spots to					60	P			
	4 spots sponged/jetted now					<20	P			
	all areas now seem to be close					<20	P			
	to background being 70-80 cps(P)									
	PRDO station to be									
	resurveyed in B12 EFC prior									
	to being cleared to a clean									
	area. DP									

Survey completed by: DPowell	Date 27 2 98	HP Supervisor's Comments:	α C:
HP Supervisor:	Date		β C:
RPS or Area Supervisor:	Date		– R:

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well entrained in to the surface of the steel. Further sponge-jet cleaning left only 6 spots up to 80 c.p.s.. To detect these spots a 'mincon' probe (- trade name standing for 'mini-contamination', a relatively cheap type of hand-held monitor used to detect radiation from light contamination) was used which is less sensitive to background γ radiation from the cave roof area outside the enclosure, due to the configuration of the detector tube. Grinding was attempted on these remaining spots due to their apparent localised nature. This was slow and laborious since the grinder is very localised in action and the contamination may well be an isolated particle. The areas were marked clearly and then sponge blasted in the same area for a period of up to several minutes. This reduced all areas to <20 c.p.s. by 'minicon' probe. These levels were in fact lower when examined in the lower background radiation areas of site.

The second PRDO station had similar levels of contamination being part of a functioning flask posting station for many decades. On the other hand a third cylinder was never used for flask handling, but had been used as a convenient storage area for contaminated items, taking advantage of the shielding it afforded. It nevertheless required decontamination back to bare metal to ensure it was clean. At the end of the LLW trial three steel cylinders had been cleaned down to free release levels (<0.4 Bq g^{-1} and <4 Bq cm^{-2}). A total of ~43.65 m^2 of steel surface was decontaminated amounting to 22.8 tonne of steel available for reuse. By contrast Figure 4.2e presents extracts from the waste consignment declaration form showing that 385 kg of spent medium was sent for LLW disposal to Drigg. Since $1m^3$ of new Silver medium weighs ~535 kg, this amounts to approximately ~0.7 m^3 of new medium. This would equate to nearly 17 bags of new medium, but only 15 bags of new medium were used weighing 345 kg (23 kg per bag). As noted earlier in section 4.1 the medium volume reduces considerably as it breaks up, and this medium

was recycled to exhaustion. It also gains weight from the contaminants it abrades from the metal surfaces being cleaned. In the initial trials a weight increase of 8.7% was observed in the spent medium after 5 recycles. The LLW trial on the PRDO stations corresponds to an increase of 11.6%. Since much of the medium has been recycled more than 5 times during the LLW trial, and there may be some additions for the extra polythene bags containing the medium, this may be considered to be broadly consistent with the initial trials.

The initial trials estimated that a single 115 kg load of medium (5 x 23 kg bags) recycled five times would provide approximately 1 hour 44 minutes of blasting at maximum pressures. This would be expected to clean ~9.34 m^2 at a 150 mm stand-off, or ~21.79 m^2 at a 300 mm stand-off. Therefore the medium used in the LLW trials should have provided at least 5 hours 12 minutes of blasting time, leading to a potential decontamination area of between 28 m^2 and 65 m^2. Since the three PRDO stations amount to a total area of 43.65 m^2, the medium was recycled more than five times and the stand-off was variable, this is broadly consistent with initial observations. The three cylinders occupy a minimum cubic space of ~10 m^3 which would attract waste disposal costs of ~£30k (assuming ~£3k m^{-3}). The uncompacted spent medium volume was ~0.65 m^3, attracting a disposal cost of ~£1950. This could be reduced to £650 if a volume reduction of 3 to 1 is gained prior to disposal. If the capital costs of the LLW system are ignored, taking account of labour (15days x 3 operators x £200/day tariff) and material (~£1000), this equates to a potential cost saving of ~£1800 m^{-3}.

Improvements in the time it took to clean each cylinder were made by adapting to the lessons learnt from cleaning the first station as well as the operators being more familiar

FIGURE 4.2e: BAGS OF SPENT SPONGE FOR LLW DISPOSAL TO DRIGG FOLLOWING PRDO DECONTAMINATION

Sellafield Generator's LLW Declaration Form - Individual Wastestream/Cost Centre Sheet

Sheet No: N°2 | Waste Stream No / Suffix: ...../..... | Container Type and Serial No: ...../..... | Sequential Plant Record No: ...../.....

Cost Centre: VMAE | Job Number ..... | Activity Assessment Basis (AAB) Units: ..... | Sequential B38C Record No: ...../.....

Item No.	Description (Be as accurate as possible and include measurements if appropriate)	Weight (Kg)	Volume (m^3)	Av. γ radiation (μSv/hr)	AAB measurement	Monitoring Signature	Plant Use Only		
41	WASTE ADDITEX	9		1		V.A			
42	PAPER CLOTHS	2		1		V.A			
43	SISAL PAPER GLOVES	5		1		V.A			
44	BROKEN GLASS IN PAINT CAN	15		12		V.A			
45	—" —	13		8		V.A			
46	BROKEN GLASS IN PAINT CAN	7		2		V.A			
47	—" —	18		4		V.A			
48	BROKEN GLASS IN PAINT CAN	21		2		V.A			
49	—" —	20		1		V.A			
50	BROKEN GLASS IN PAINT CAN	23		2		V.A			
51	—" —	21		1		V.A			
52	BROKEN GLASS IN PAINT CAN	25		2		V.A			
53	FOAM	30		1		V.A			
54	FOAM	11		1		V.A			
55	FOAM	20		1		V.A			
56	FOAM	16		1		V.A			
57	FOAM	9		1		V.A			
58	FOAM	14		1		V.A			
59	FOAM	14		1		V.A			
60	FOAM.	22		1		V.A			
TOTAL Side 1	Carry over totals to side 2.								

SIGN ID

Use a separate Wastestream sheet for each combination of Wastestream / Cost Centre / Job No.

Figure 4.2e. Continued

Sellafield Generator's LLW Declaration Form - Individual Wastestream/Cost Centre Sheet

Item No.	Description (Be as accurate as possible and include measurements if appropriate)	Weight (Kg)	Volume (m^3)	Av. γ radiation (μSv/hr)	AAB measurement	Monitoring Signature	Plant Use Only		
21 61	FOAM.	21		1		V.A			
22 62	FOAM	27		1		V.A			
23 63	FOAM	16		1		V.A			
24 64	FOAM	17		1		V.A			
25 65	FOAM	27		1		V.A			
26 66	FOAM.	10		1		V.A			
27 67	FOAM.	11		1		V.A			
28 68	FOAM.	11		1		V.A			
29 69	FOAM	18		1		V.A			
30 70	FOAM	27		1		V.A			
31 71	FOAM	9		1		V.A			
32 72	FOAM	5		1		V.A			
33 73	FOAM	12		1		V.A			
34 74	FOAM	38		1		V.A			
35									
36	TOTAL WT	385 kgms		of Foam					
37									
38									
39									
40									
TOTAL Side 2									
TOTAL Side 1									
GRAND TOTAL									

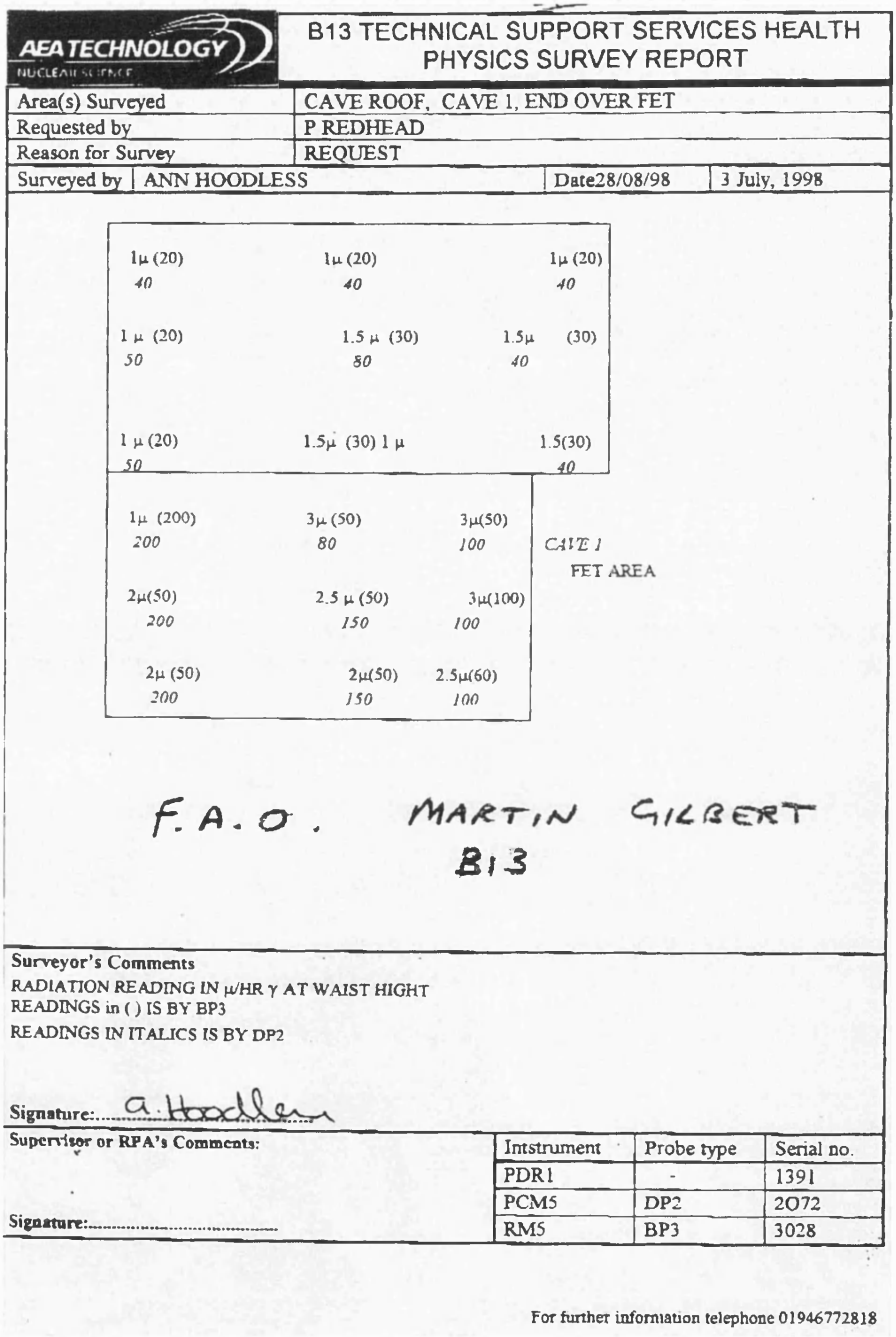
This is Side Two of the Sellafield Generator's LLW Declaration Form - Individual Wastestream/Cost Centre Sheet. It should only be used if Side One is full. Additional data is filled in on Side One which is omitted from this side.

Use a separate Wastestream sheet for each combination of Wastestream / Cost Centre / Job No. 2

with the Sponge-jet system. To speed up the LLW decontamination process required a number of improvements, one of which was the approach to recycling. The recycle-ability of the medium is central to the viability of this LLW decontamination process. This initially involved manual collection using a broom and shovel during the PRDO cleaning. The recycle process on the first cylinder took more than twice as long as the actual blasting process itself. Trials were conducted on the second cylinder using a vacuum cleaner, to try and 'hoover' spent medium into a metal bin that could then be discharged quickly into the grader for recycling. This improved the operations significantly and reduced dose uptake time to operators on subsequent decontaminations. Consideration should also be given to the use of vacuum collection of the medium, incorporating an automated separation and recycling system. This will also help to reduce occupational dose uptake by further minimising the exposure time from grading the medium when decontaminating LLW. Trials to develop a higher activity test rig for in-cave use may have spin-offs that may be utilised to enhance the LLW system.

After the trial other improvements were progressed to address the problems of raised background radiation levels and the detection of such low levels of contamination. The enclosure floor and half way up the side-walls were clad with shielding in order to bring these background radiation levels down. Another approach was to develop shielding for the monitoring probes, such that the detectors were more directional receiving radiation only from the surface being cleaned. Figure 4.2f shows how the probe shielding reduces the radiation measured generally in the cave roof area and within the enclosure. These improvements culminated in a LLW decontamination facility that was utilised as fully operational process not just to carry out decontamination trials.

FIGURE 4.2f: RADIATION MEASUREMENTS IN THE CAVE ROOF AREA IN AND AROUND THE ENCLOSURE WITH AND WITHOUT PROBE AND ENCLOSURE SHIELDING



AEA TECHNOLOGY
NUCLEAR SCIENCE

B13 TECHNICAL SUPPORT SERVICES HEALTH PHYSICS SURVEY REPORT

Area(s) Surveyed	CAVE ROOF, CAVE 1, END OVER FET		
Requested by	P REDHEAD		
Reason for Survey	REQUEST		
Surveyed by	ANN HOODLESS	Date28/08/98	3 July, 1998

1μ (20) *40* | 1μ (20) *40* | 1μ (20) *40*

1 μ (20) *50* | 1.5 μ (30) *80* | 1.5μ (30) *40*

1 μ (20) *50* | 1.5μ (30) 1 μ | 1.5(30) *40*

1μ (200) *200* | 3μ (50) *80* | 3μ(50) *100*

2μ(50) *200* | 2.5 μ (50) *150* | 3μ(100) *100*

2μ (50) *200* | 2μ(50) *150* | 2.5μ(60) *100*

CAVE 1
FET AREA

F.A.O. MARTIN GILBERT
B13

Surveyor's Comments
RADIATION READING IN μ/HR γ AT WAIST HIGHT
READINGS in ( ) IS BY BP3
READINGS IN ITALICS IS BY DP2

Signature: A. Hoodless

Supervisor or RPA's Comments:

Signature:

Intstrument	Probe type	Serial no.
PDR1	-	1391
PCM5	DP2	2072
RM5	BP3	3028

For further information telephone 01946772818

Radiation measurements in and around the LLW enclosure using DP2($\mu Sv\ hr^{-1}$) , and BP3(c.p.s.) probes before modifications

Figure 4.2f. Continued

B13 Cave roof Spongeyet hut | Supervised | Special/Request ✓ | RMS [redacted] 2537 ✓ | Non-designated | Reclassification | B83 1805 ✓ | Other

No.	Details (include background if significant) Background *all readings at waist height	Radiation (circle units) µSv/h βγ	γ	mSv/h n	Contamination (circle units) Bq/cm² α	βγ	CPS P/S	U/S S or K	Start Time	Comments or Diagram:
	Outside of spongeyet hut probe horizontal									*with shield in place probe is 12 cm further away than no shield.*
	window open no shield					15	P			
	shield in place					5	P			
										*Shielded probe had not been calibrated with RMS.
	Inside hut horizontal window open									
	no shield					15	P			
	shield in place					5	P			
										Unshielded probe was calibrated.
	Probe facing green bar at contact									
	in bar no shield					12				
	shield in place					2				

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Radiation & Contamination Survey Report
Health Physics Services

Date:	Building:	Designation	Radiation	Contam.	Type of Survey (tick)	Instruments used	Serial No.	Tested	Survey No.
12/15-4-99	B13								
Area Surveyed:		Controlled			Routine				
CAVE ROOF		Supervised			Special/Request ✓	RMS RP2	1556	✓	
SPONGE-SET HUT.		Non-designated			Reclassification				
					Other	SCALER	N°8		

No.	Details (include background if significant) Background	Radiation (circle units) µSv/h βγ	γ	mSv/h n	Contamination (circle units) Bq/cm² α	βγ	CPS P/S	U/S S or K	Start Time	Comments or Diagram:
	FLOOR AREA									
	PROBE WITHOUT SHIELDING -					60	(P)			
	" WITH SHIELDING -					20	(P)			
	WAIST HEIGHT -									
	PROBE WITHOUT SHIELDING -					80	(P)			
	" WITH SHIELDING					50	(P)			

Radiation measurements after enclosure modification and use of probe shielding showing how background can be reduced.

Non-abrasive Decontamination of Milling Tool

This assessment considers the radiation dose from the machine before during and after decontamination. The milling machine would occupy at least 1 m^3 in terms of volume, that means a waste cost of at least £3k m^{-3}, but there may have been a possibility that the machine might exceed the fissile limits thus making it ILW and therefore much higher disposal costs could be incurred. So there was a substantial incentive to decontaminate and retool what is a perfectly reusable machine rather than dispose of it and buy a new one. Unfortunately to retool such a machine would require some considerable 'hands-on' time, working on the machine tool. In order to meet with the requirements of ALARP [62], some form of decontamination or innovative working would be required, otherwise substantial or prohibitive personnel dose uptake would be involved. Due to the complexity of the machine conventional decontamination techniques would themselves, require close 'hands-on' work to clean the machine down using tissue swabs. The Sponge-jet process was given an opportunity to try and reduce the dose rates to a level that may allow adequate working time on the machine tool with out incurring excessive dose uptake. Due to the critical nature of many surfaces on the machine tool this trial was conducted to evaluate the use of the Green non-abrasive sponge medium. The following summarises the data collated during this exercise;

1. Milling machine was removed from cave and placed in the LLW enclosure and had radiation dose rates of up to 18 mSv hr^{-1} $\beta\gamma$, and 6 mSv hr^{-1} γ at distances up to ~150mm as measured using RO2 rate meter.

2. One Health Physics monitor attempting to decontaminate the machine with damp tissues incurred a dose uptake of 116 μSv. This involved approximately 15 to 20

minutes in the enclosure, and a number of quick approaches to the machine to wipe what appeared to be the highest radiation areas followed by withdrawal. The dose rates reduced to 3 mSv hr^{-1} $\beta\gamma$, and 500 μSv hr^{-1} γ. One exception was the lead screw that still had radiation levels up to 10 mSv hr^{-1} $\beta\gamma$, and 1.5 mSv hr^{-1} γ.

3. The machine was then blasted with non-abrasive green medium for ~15 minutes and appeared to achieve a decontamination factor of between 4 and 5. This was achieved by standing back (a ~1 to 1.5 m distance) and directing the blast over the machine tool, while paying more attention to the more highly contaminated areas. Operator dose uptake was 50 μSv as a result of this distance from the radiation source even though the same time was spent in the enclosure, the effective wiping action was increased from little more than a minute with manual wiping (Health Physics monitor) to ~15minutes. Residual dose rates were ~0.67 mSv hr^{-1} $\beta\gamma$, and ~0.11mSv hr^{-1} γ at distances up to ~150 mm.

4. The maintenance technician worked on the machine for nearly one hour to effect all refurbishments/repairs and retooling. This incurred a dose uptake of 0.35 mSv. Slideways, screw threads and gearing were degreased without damaging the bearing surfaces.

Airborne radioactivity levels were quite high for this level of decontamination, which demonstrates that manual decontamination, even using Sponge-jet and full radioactive personal protective equipment, can not be sustained for cleaning tooling and equipment in the enclosure. Notwithstanding the results of this trial, if a system could be developed where by the Sponge-jet technique could be deployed within the WAHF cave system,

dose uptake would be dramatically minimised. If a suitable system could be developed for decontamination of higher radioactive waste, it might be possible to adapt the process for dual use and assist in the general maintenance work within the facilities, while at the same time reducing the personnel dose uptake of the operators. The overall benefits of waste disposal cost saving for this specific tool amount to ~1 m^3 or ~£3k, plus the cost of a replacement tool which is conservatively estimated to be at least £2k.

4.2.2 LLW Media Studies

An SEM examination of active sponge media from the LLW trials was carried out on media taken after the control area trial. Samples of Silver medium were taken after a single pass, where no grading was involved and the samples were collected directly from the floor of the enclosure to minimise handling disturbance and any loss of contaminants. The samples were prepared for the SEM examination using Silverdag® to attach a selection of granules to an aluminium stub. The samples were then sprayed with a carbon suspension to allow conduction from the surface of the insulating granules to the specimen holder. The samples were then examined using a Jeol T220A SEM in a glovebox. All investigations were carried out at 20 kV.

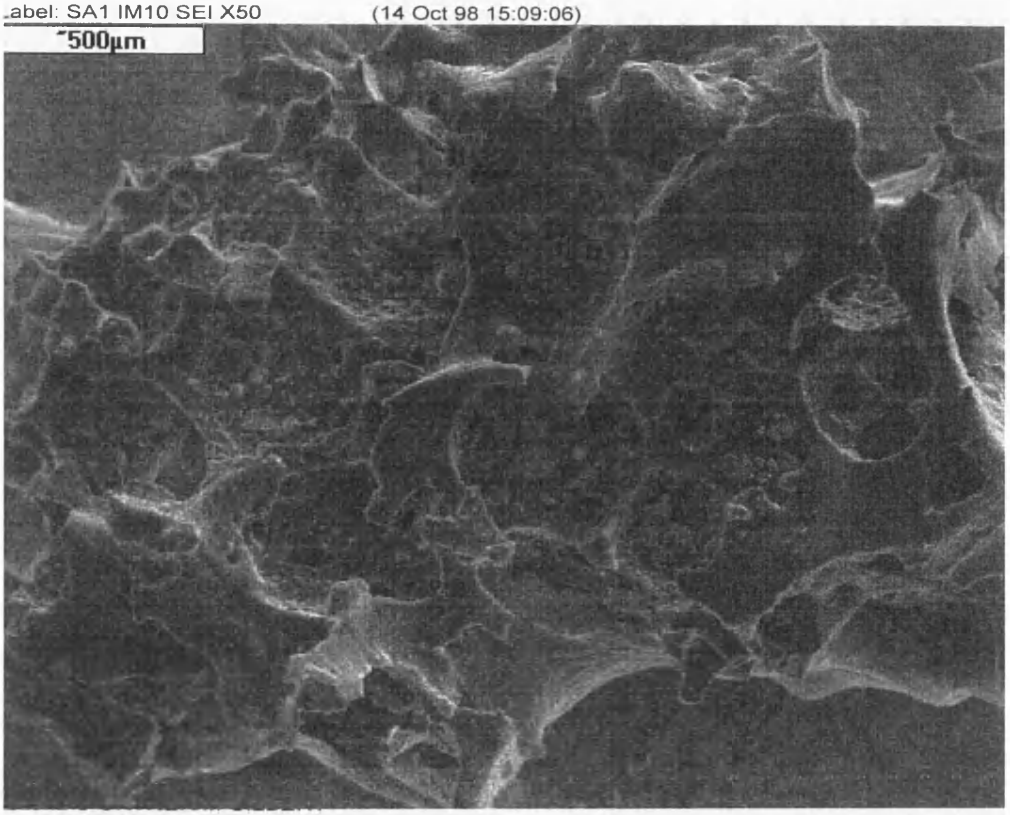
While the matrix of this medium appeared damaged, the alumina grit particles were less fragmented than after the longer (more recycled) inactive trials. Large alumina particles were still observed, partly embedded in the polyurethane matrix. Large numbers of smaller particles were also observed on the sponge surface. These particles appeared to have been picked up from the cleaned PRDO station surface. These particles were largely iron and iron oxide (presumably from the rust layers at the ends of the cylinders), but a small fraction contained elements such as yttrium (Y), strontium (Sr), barium (Ba) or Lead (Pb). These elements could have originated from fuel posting operations, or

shielding when the PRDO stations were in operation. The Ba particles may have originated from liquid spillages from water contained in the flask. Pond and flask water was often dosed with Ba since it acts as a moderator, enhancing the neutron moderating properties of the water.

Figure 4.2g shows one particle in successively more detail revealing damage to the polyurethane webs between cells, and the fine particles covering the surface of the matrix. The last micrograph shows these fine particles in better contrast as a Back Scattered Electron (BSE) image, where the lighter particles are predominantly Fe-rich, with some smaller Pb-rich particles. Figure 4.2h. shows the presence of AlO particles still retained by the polyurethane matrix. Again using the BSE image it shows the brighter Fe-rich particles. Some particles on the matrix of the sponge are the shattered remnants of these AlO grit particles as shown by the large particle in the third micrograph.

FIGURE 4.2g: SEM MICROGRAPHS OF SILVER MEDIA FROM LLW TRIAL

Job: MCMP199 T17 SPONGE MEDIUM
Res: Ultrafine
Label: SA1 IM10 SEI X50 (14 Oct 98 15:09:06)



Job: MCMP199 T17 SPONGE MEDIUM
Res: Ultrafine
Label: SA1 IM4 SEI X100 (14 Oct 98 11:49:23)

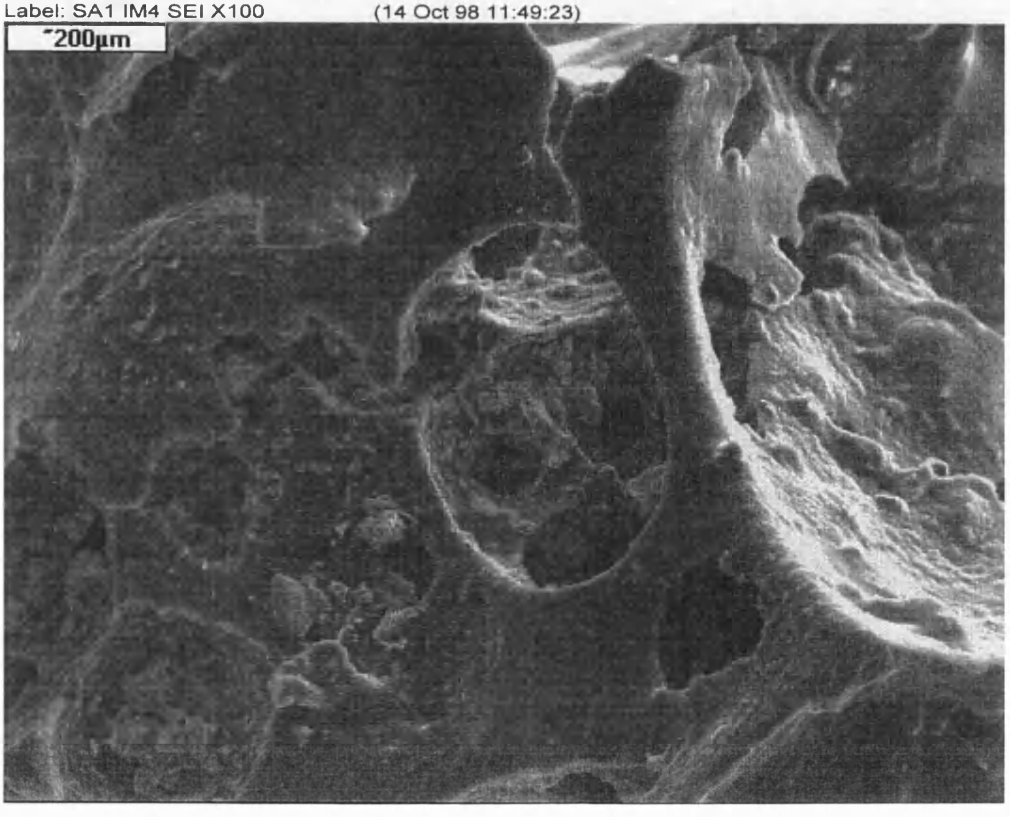
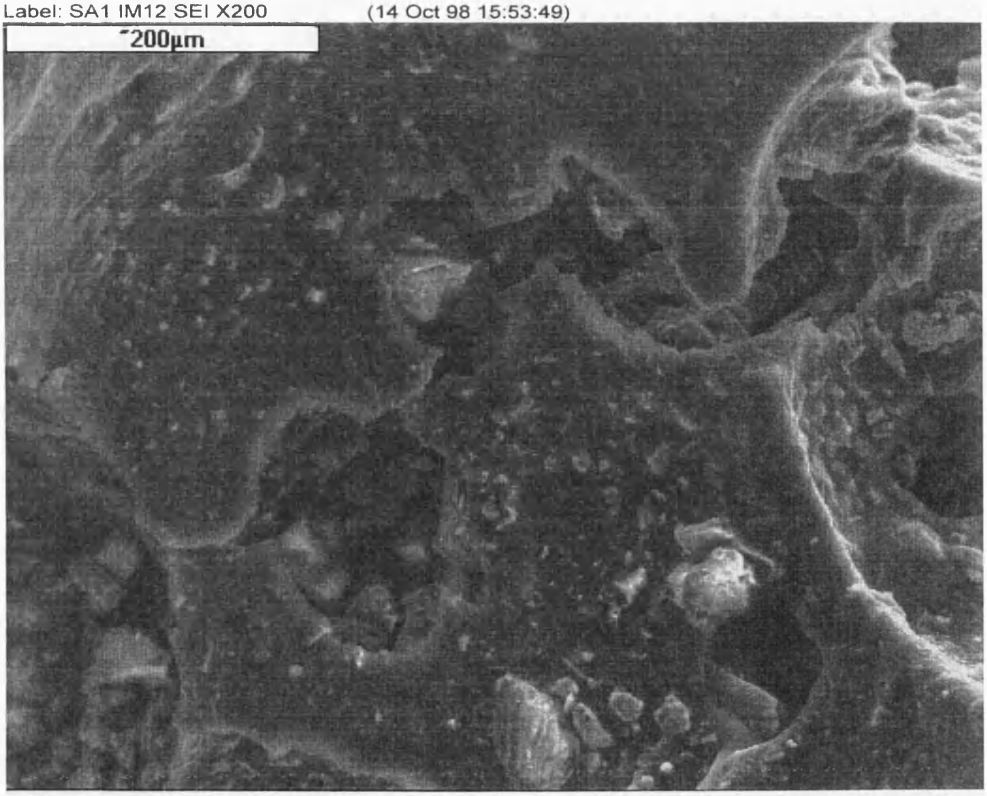


Figure 4.2g. Continued.

Job: MCMP199 T17 SPONGE MEDIUM
Res: Ultrafine
Label: SA1 IM12 SEI X200 (14 Oct 98 15:53:49)



Job: MCMP199 T17 SPONGE MEDIUM
Res: Ultrafine
Label: SA1 IM3 BSE X1000 (14 Oct 98 11:45:05)

FIGURE 4.2h: ALUMINIUM OXIDE GRIT STILL HELD BY THE POLYURETHANE MATRIX

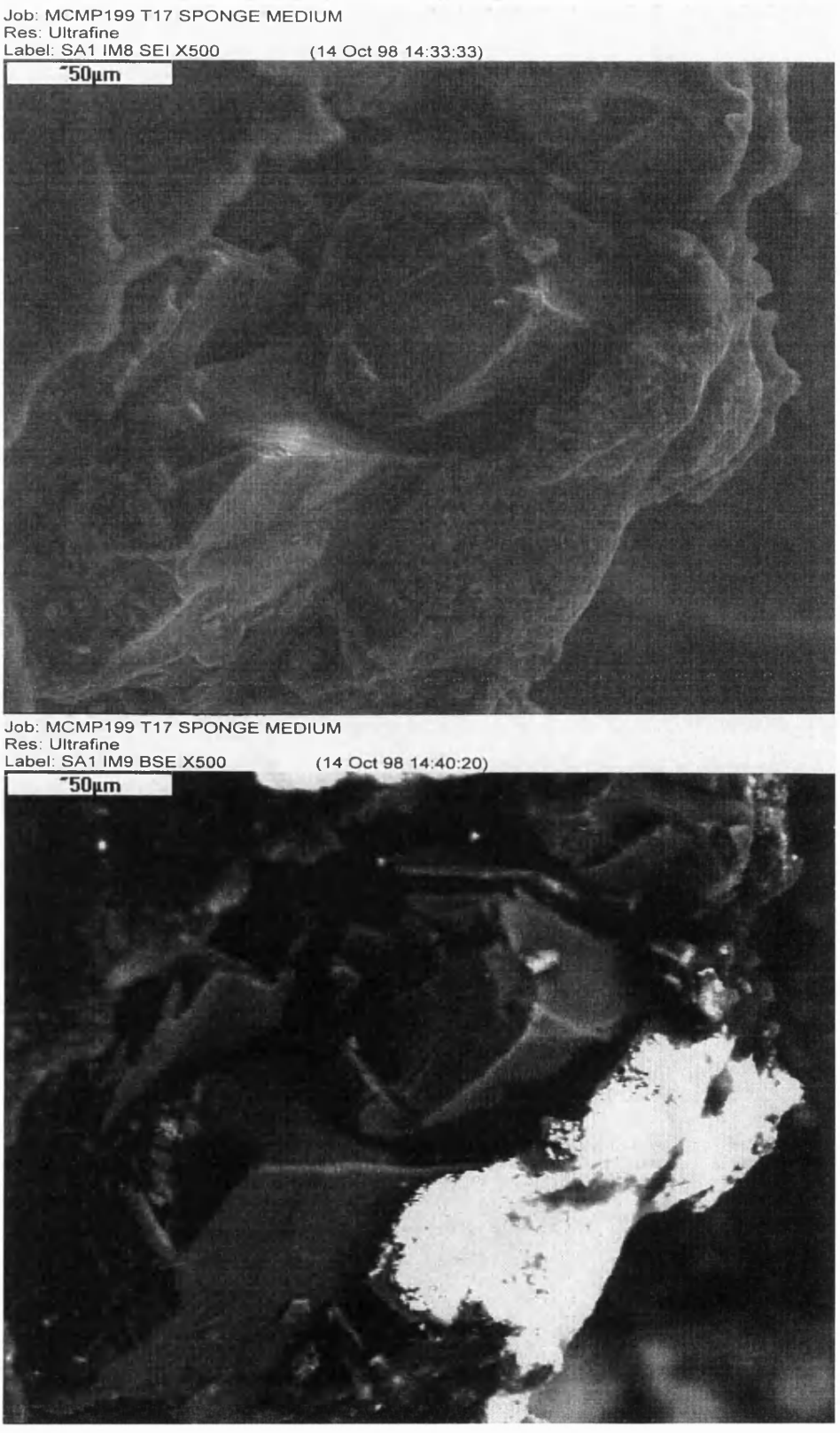


Figure 4.2h. Continued

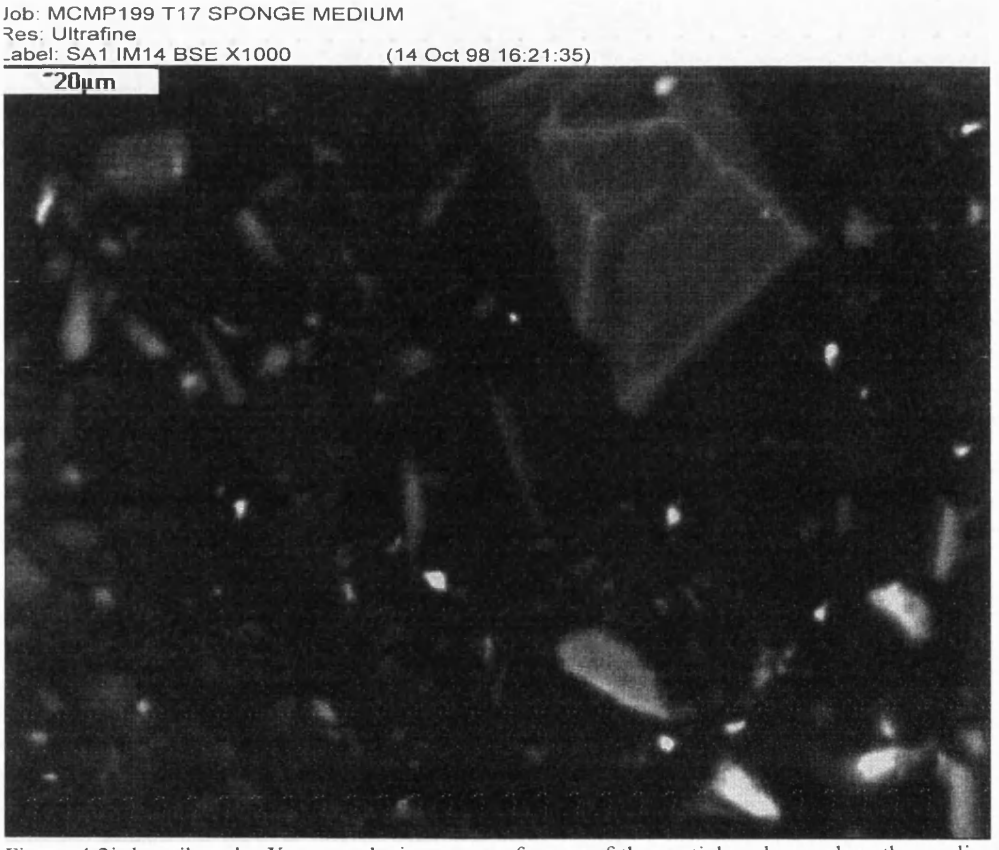


Figure 4.2i describes the X-ray analysis spectra of some of the particles observed on the media used in the active LLW trial on PRDO stations.

FIGURE 4.2i: X-RAY ANALYSIS SPECTRA FOR SOME PARTICLES FOUND ON THE MEDIA USED IN THE LLW TRIALS

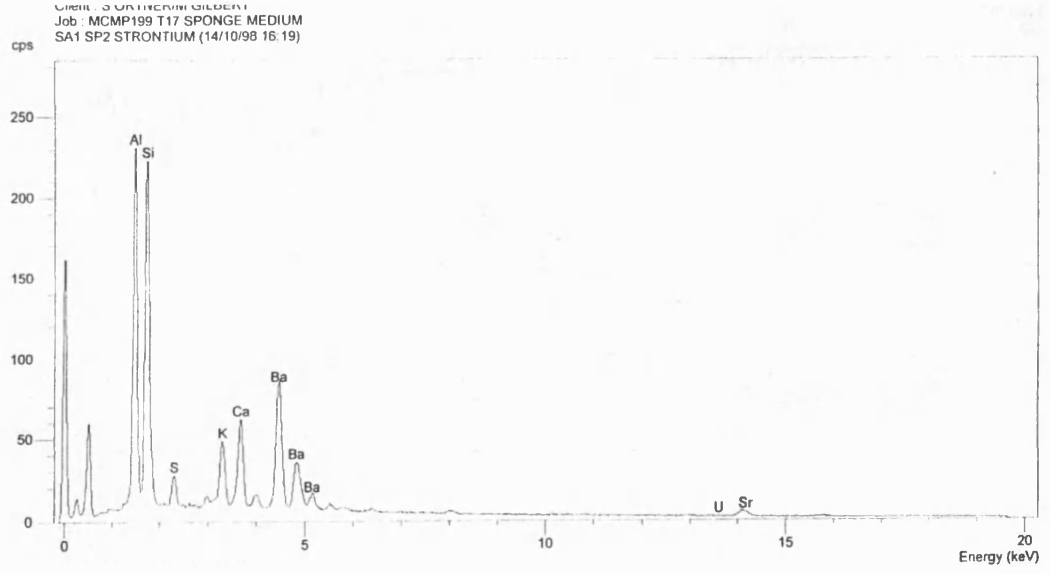
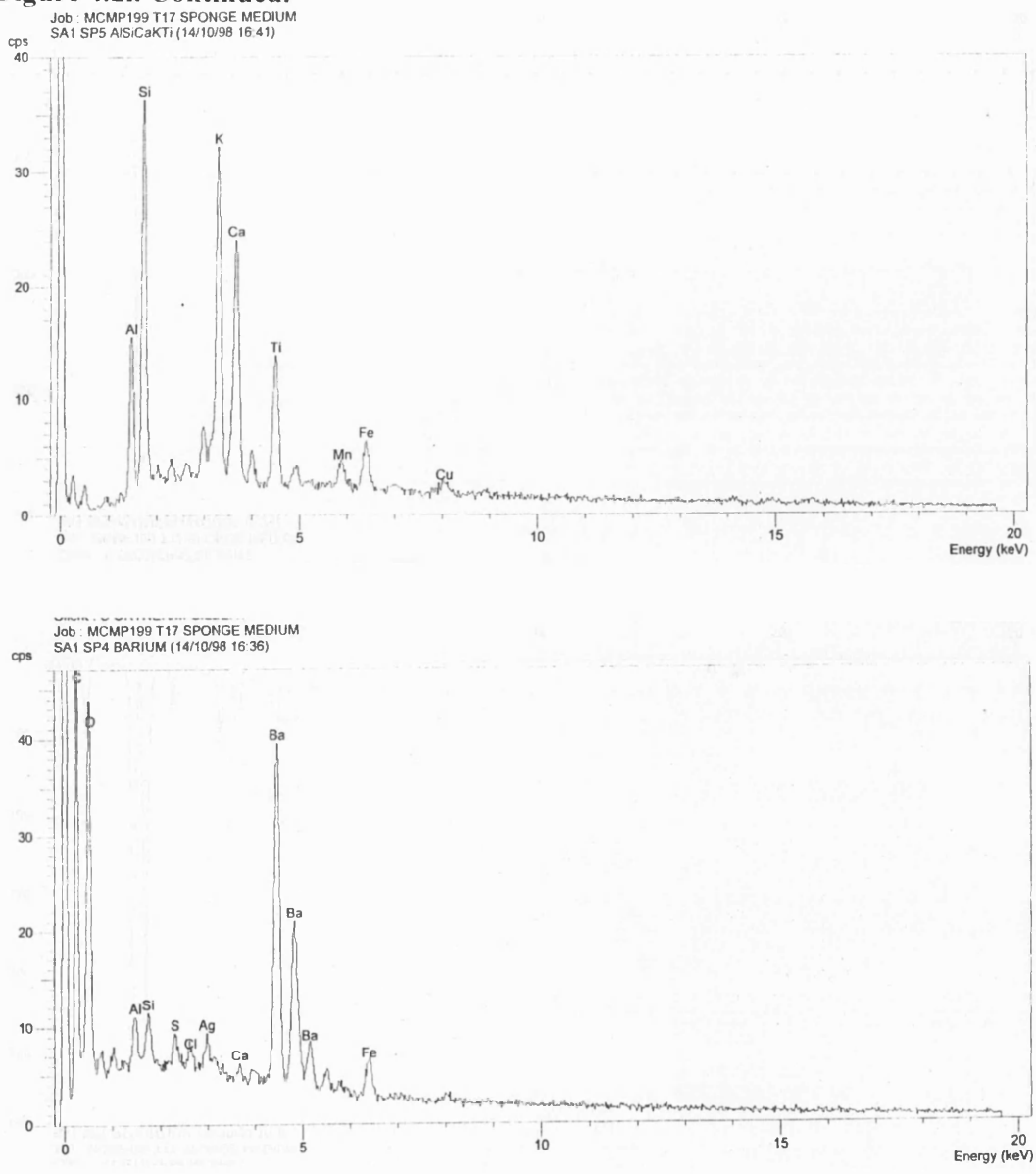


Figure 4.2i. Continued.



4.2.3 Media Volume Reduction

Samples of polyurethane gaiter material were taken from the four positions described in Chapter 3.1, and placed in sealed containers within a gamma radiation field near a Uranium fuel store in one of the WAHF caves (see Figure 3.1m).

Three sets of samples from each of the positions were individually and separately packaged as described previously, so that one set of samples could be retrieved following known periods within the radiation field. One set (set A) was retrieved after two months exposure, the next set (set B) after 4 months exposure, and the last set (set C) after 6 months exposure. Taking account of this and the mean volume of fuel stored, decay since discharge, fuel irradiation time and burn-up and distance of the samples from the fuel it is possible to make a rough estimation of the radiation dose received by the samples. It is estimated that sample set A will have received ~72 kSv, sample set B will have received ~144 kSv and sample set C ~216 kSv. It is considered that these doses represent a worst case since the gaiters are never entirely this close to the radiation source, and then only during the operational periods when the cuffs of the gaiter will experience higher doses depending on what is held by the MSM. It is estimated that these doses probably reflect the overall dose received by a worst-case gaiter in 1, 2 and 3 years, respectively. It should be recognised that the spent gaiter will receive ongoing dose from contaminants long after its operational use, into long term storage and eventual disposal. For most gaiters this dose uptake could represent as much as 10 years dose. Therefore the degradation characteristics of the polyurethane under this radiation may provide some information on the longer-term properties of the material as a waste form.

As with the initial trials on as-received polyurethane gaiter material the samples were studied using IRS, DSC and weight loss techniques. The preparation techniques are the

same as before, and with the exception of the IRS technique all the experiments were undertaken on the same apparatus and equipment. Problems were encountered with the Perkin Elmer FTIR spectrometer after studying the sample set A so subsequent samples were examined on Philips double beam spectrometer, model number PU9700.

The IRS spectra graphs (both Perkin Elmer and Philips) for the radiation-damaged samples confirm that the material is the same material tested in the undamaged, or as-received samples (see Figure 4.1r). There are no obvious changes with radiation damage that can be observed in these spectra. The polyurethane samples were observed to exhibit a greater degree of discolouration with increasing radiation damage, to the level where they look charred after six months exposure. These samples also became more brittle to the degree that the last two samples, C3 and C4, could not be pressed without the sample disintegrating, which is why there are no spectra for these samples [93].

The DSC plots for the radiation damaged polyurethane samples do show some changes with radiation exposure. The step change in heat flow from ~65°C that was quite marked in the as-received samples, appears to flatten out and almost completely disappear with radiation exposure [93]. This is most noticeable with the corrugated lower samples of gaiter. It could be speculated as to whether the additional heat used to form the corrugated shape may have diminished the reaction seen in the graphs for the as-received samples at position 3 and 4. It would appear that previous radiation and heat affect the level of reaction at this point.

FIGURE 4.2j: INFRA-RED SPECTRA FROM SETS OF POLYURETHANE AFTER INCREASING EXPOSURE TO GAMMA RADIATION

Sample set A (Perkins Elmer IRS)

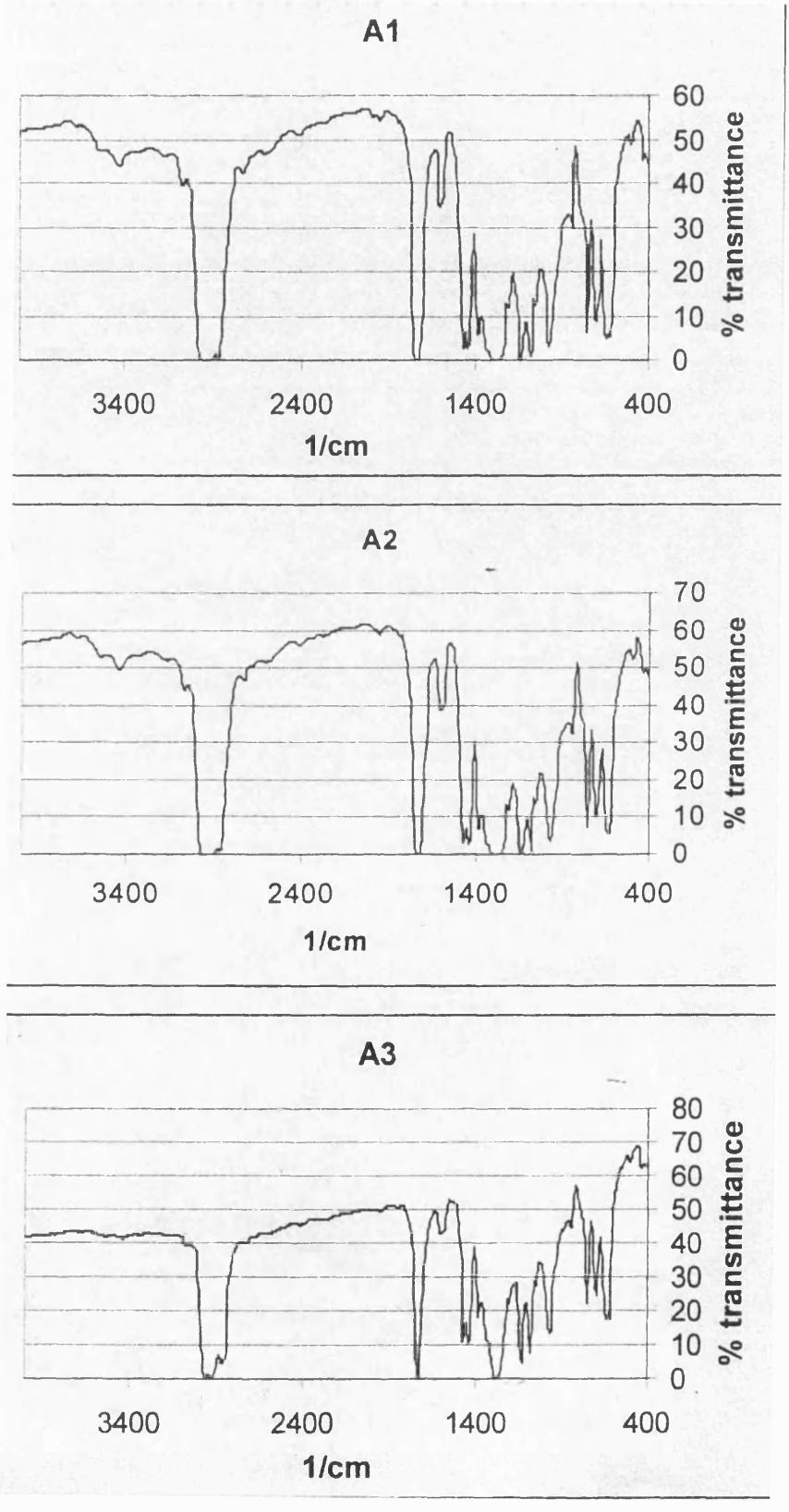
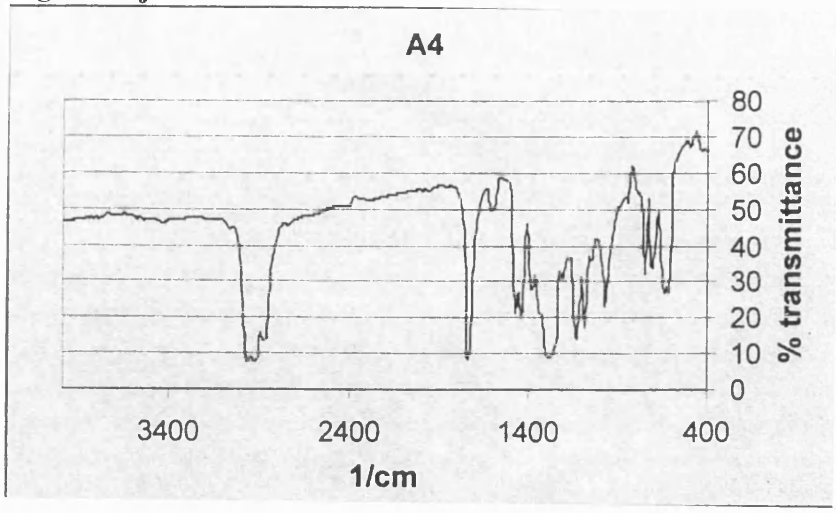
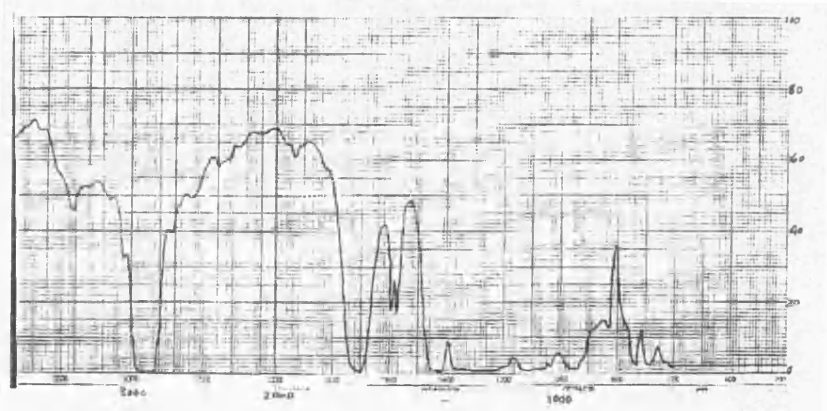


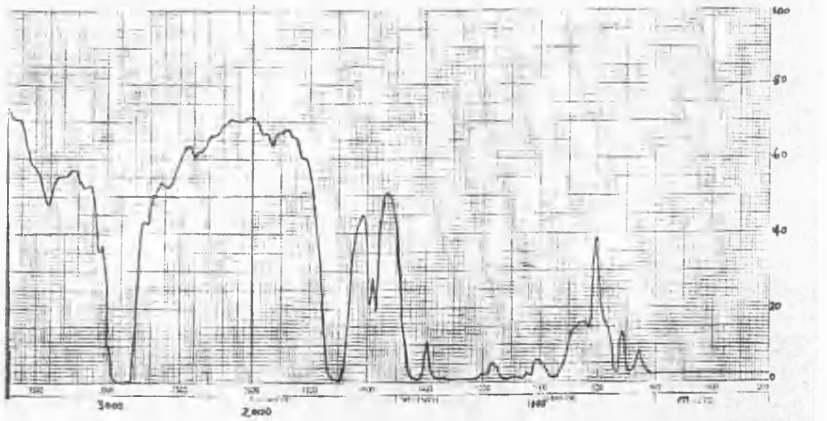
Figure 4.2j. Continued



(Philips FTIR)

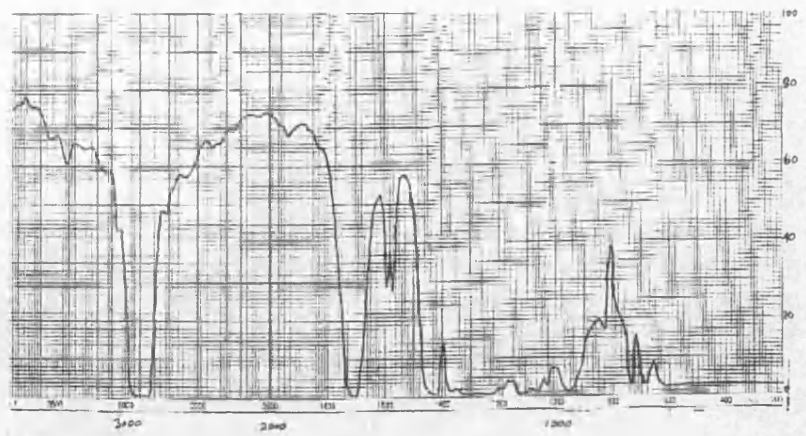


Position B1

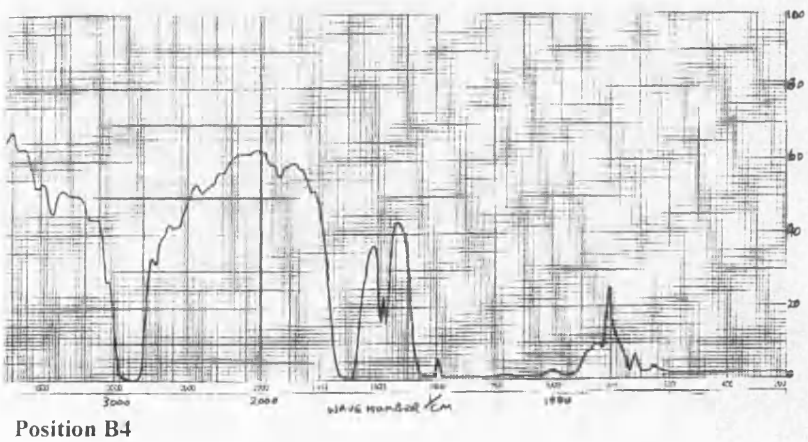


Position B2

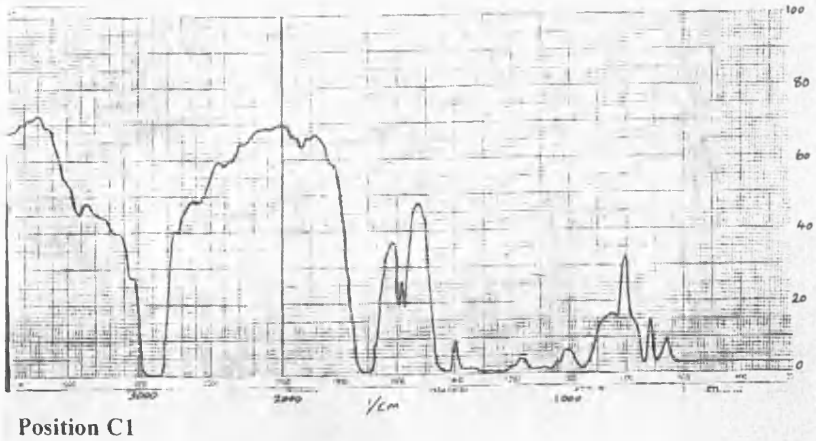
Figure 4.2j. Continued



Position B3

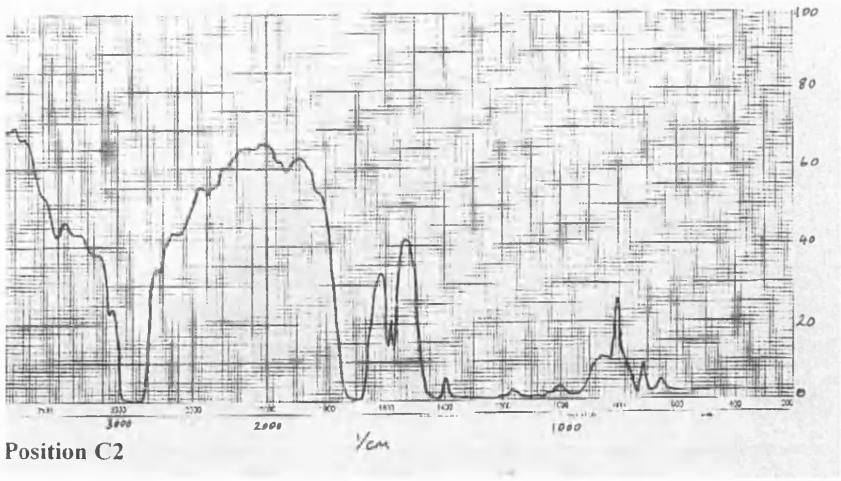


Position B4



Position C1

Figure 4.2j. Continued,

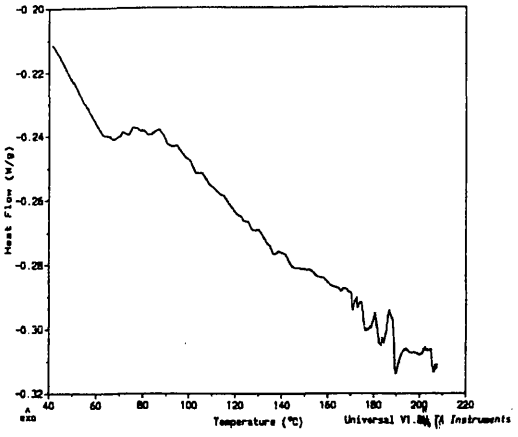


Position C2

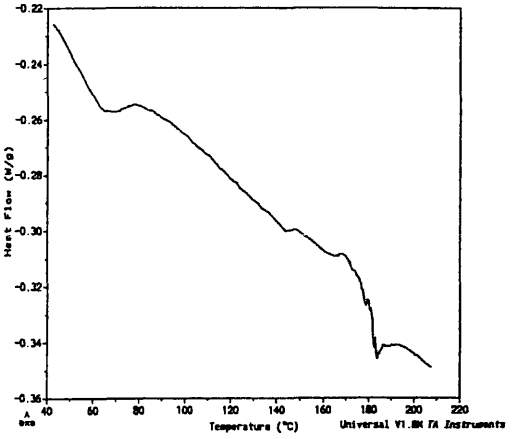
On opening the sample containers it was noticeable that they were slightly pressurised suggesting the presence of an evolved gas. The literature states that many polyurethane materials thermally degrade liberating oxygen at temperatures up to 120 °C; this is most likely to involve the breakdown of the C-O and C=O bonds [15, 17, 19, 58]. If this is the case, the prior heating involved in forming the gaiter and the in-cave radiation has damaged the relevant oxygen bonds, liberating oxygen gas, and influencing the effects seen in the DSC graphs. This leaves less oxygen bonds for breakdown during the DSC trials. This theory could be confirmed by undertaking evolved gas analysis.

Table 4.2a. and Figure 4.2l. summarise the weight loss results after heating the radiation damaged samples up to 110 °C for 21 hours. This shows that the polyurethane undergoes a small weight loss when heated, ranging from <1% (as-received), to just over 5% following severe radiation damage. The figures provide more evidence of differences in the polyurethane that makes up the upper (positions 1 and 2) and lower (positions 3 and 4). Weight losses for these positions are similar except the lower corrugated positions

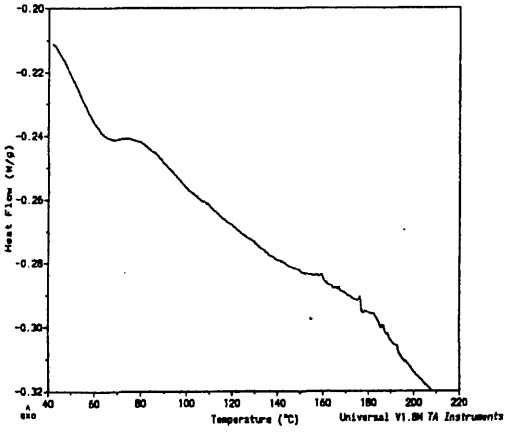
FIGURE 4.2k: DIFFERENTIAL SCANNING CALORIMETRY GRAPHS FOR SAMPLE SETS OF POLYURETHANE AFTER INCREASING EXPOSURE TO GAMMA RADIATION



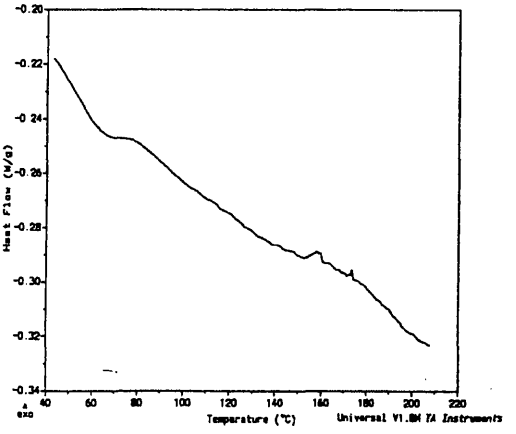
A1



A2

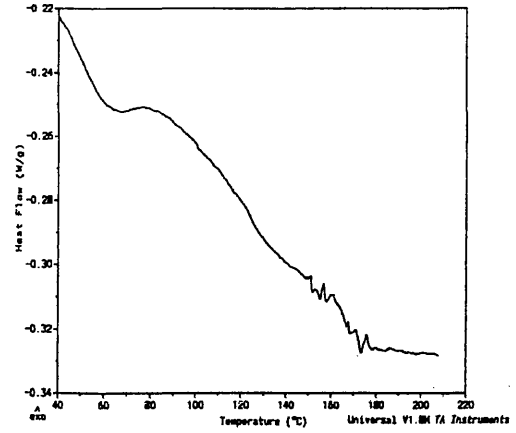


A3

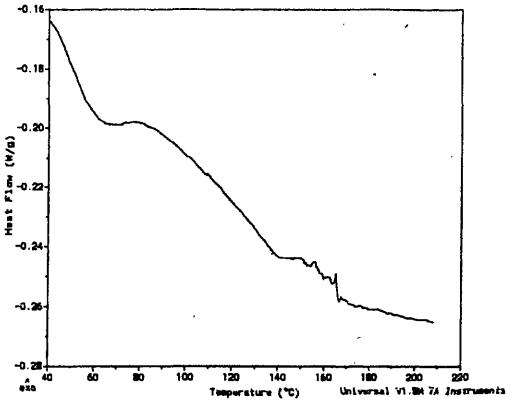


A4

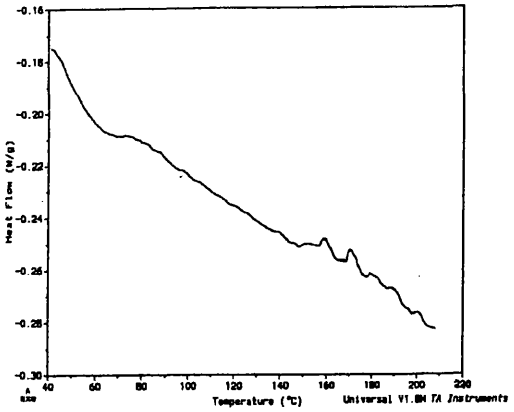
Figure 4.2k. Continued



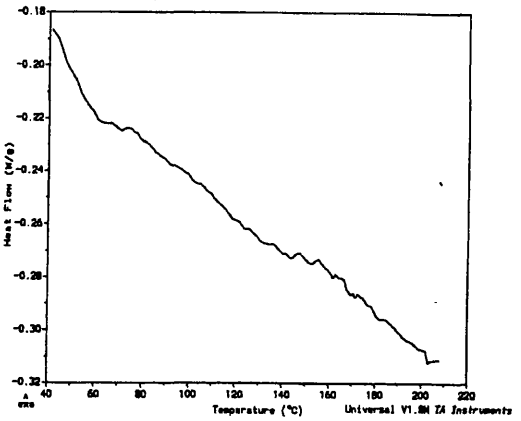
B1



B2

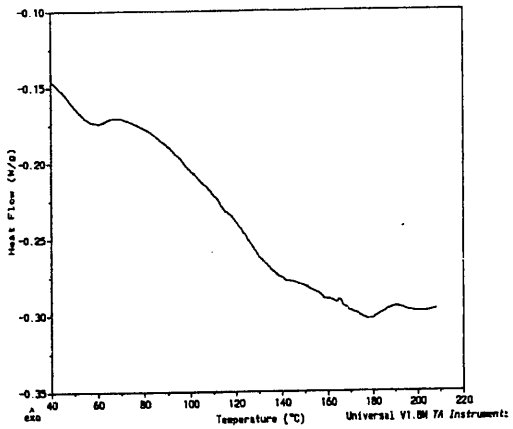


B3

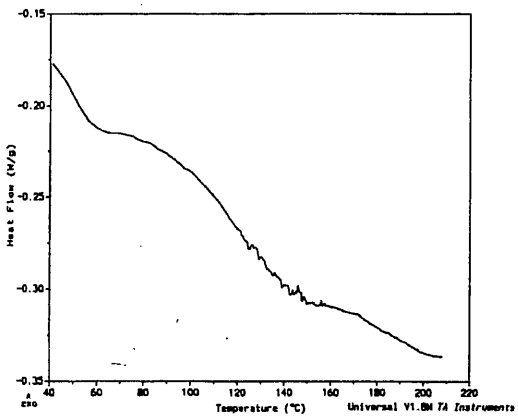


B4

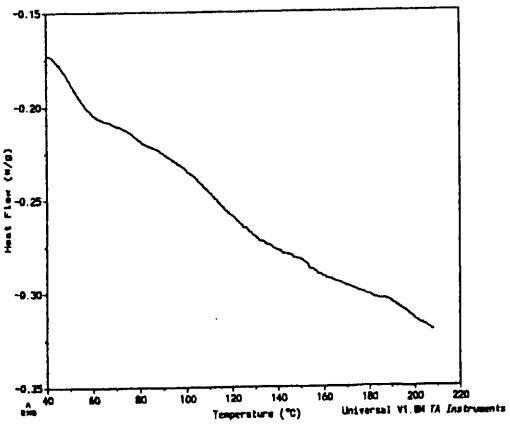
Figure 4.2k. Continued



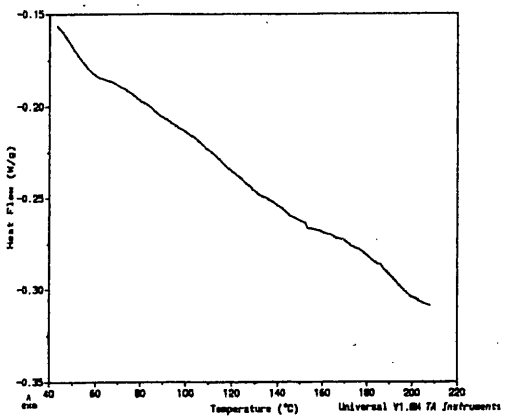
C1



C2



C3



C4

TABLE 4.2a: WEIGHT LOSS MEASUREMENTS FOR GAITER SAMPLES EXPOSED TO GAMMA RADIATION

Sample	Mass before heating (g)	Mass after heating (g)	% Weight loss
A1	0.3011	0.2989	0.73
A2	0.2358	0.2344	0.59
A3	0.3678	0.3606	1.96
A4	0.2588	0.2537	1.98
B1	0.1995	0.1963	1.60
B2	0.2273	0.2242	1.36
B3	0.3829	0.3725	2.72
B4	0.2922	0.2839	2.84
C1	0.2961	0.2822	4.69
C2	0.2484	0.2375	4.38
C3	0.3458	0.3277	5.23
C4	0.3578	0.3392	5.20

FIGURE 4.2l: GRAPH OF CHANGING WEIGHT LOSS WITH RADIATION EXPOSURE

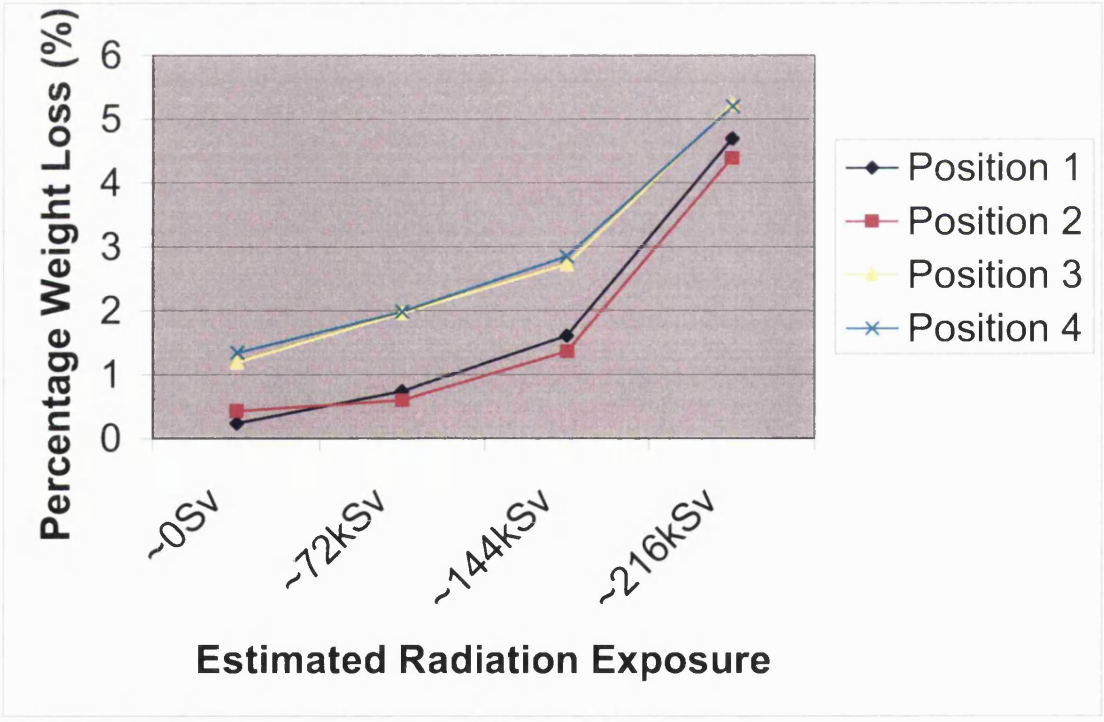


exhibit a consistently higher loss. Increasing weight loss with radiation exposure is most probably a result of chain scission, leading to increased thermal instability in the polyurethane. It is possible that the polyurethane from the lower part of the gaiter is made from a slightly different grade of polyurethane to the upper sheet film positions. This may be due to the forming process needed to create the corrugations, and could include a plasticiser.

These results suggest that volume reduction of these polyurethane materials may not create any further safety issues from adverse behaviour (i.e. excess evolution of gases) of the polyurethane during processing at temperatures up to ~200 °C in-cave at the WAHF. Further work on evolved gas analysis should be carried out to confirm this view.

Notwithstanding the above the work undertaken on developing a practical moulding process (see Section 4.1 – Volume Reduction) based on radiant heating of 'free-standing' polyurethane materials, with the aim of it melting under its own weight, appeared to fail. A new approach was required, so trials were started with the aim of exploring the possibilities of compression moulding at temperature. The problem would be to firstly determine whether it was feasible, and secondly, if it is feasible, what would be the optimum process conditions and could it be scaled up into a full size practical process for use in-cave within the WAHF. Broad [84] has shown that the Sponge-jet particles can be fused together under pressure and heat. Figure 4.2m, shows how the medium breaks down when heated beyond 220°C, during the weight loss trials. It appears that the physical changes observed, and shown in Figure 4.2m might correlate with the increased weight loss measurements observed in Chapter 4.1. Table 4.1e. This suggested that if compression moulding were to be successful it would need to be undertaken at

temperatures up to 220°C. To study such a process a test rig was developed that enabled the study of sponge strain (deflection) at different stress loading and temperatures. Figure 4.2n describes the rig and its operation.

FIGURE 4.2m: VIEWS OF MEDIA FOLLOWING WEIGHT LOSS TRIALS
Green Medium

Figure 4.2m. Continued
Silver Medium

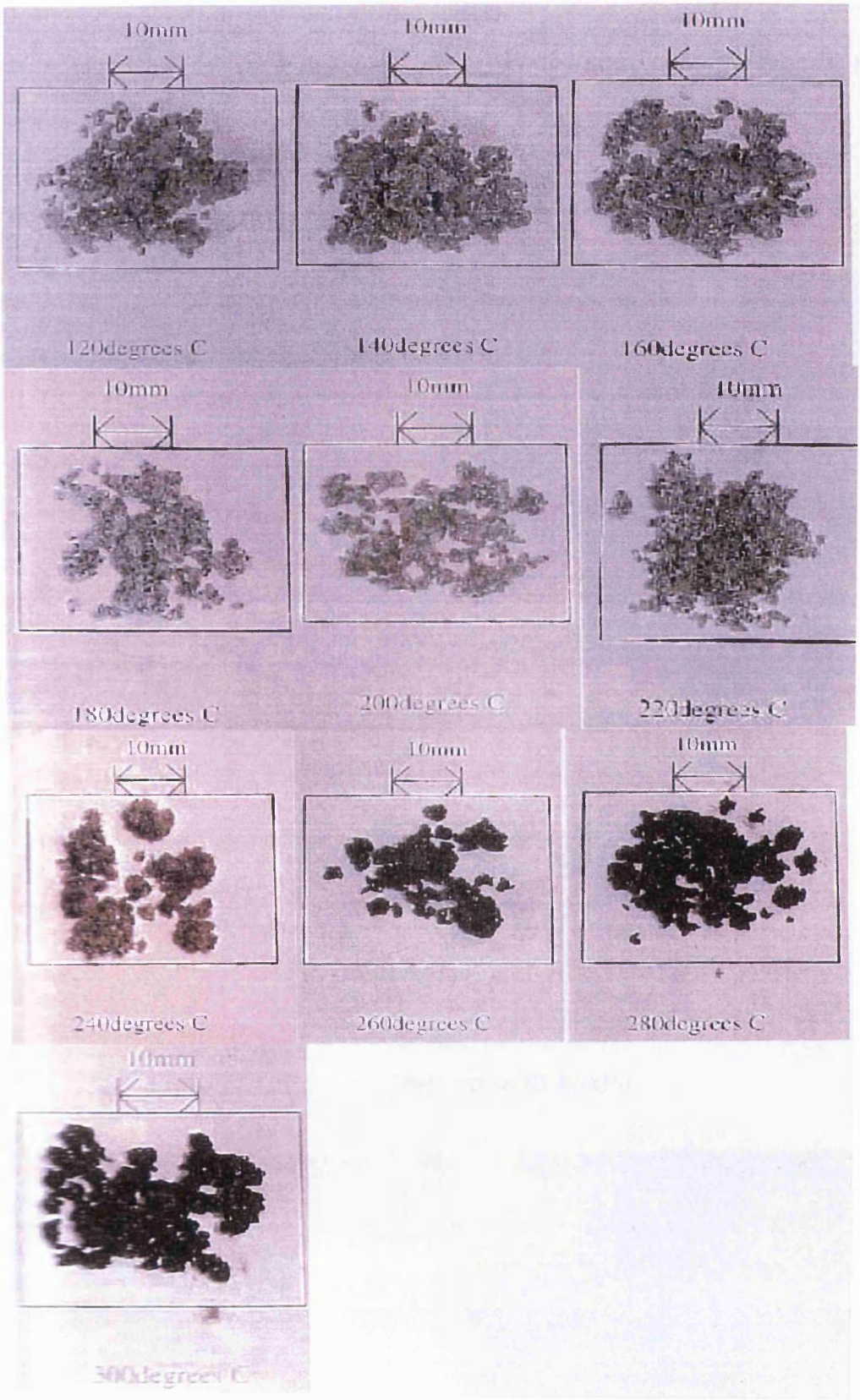
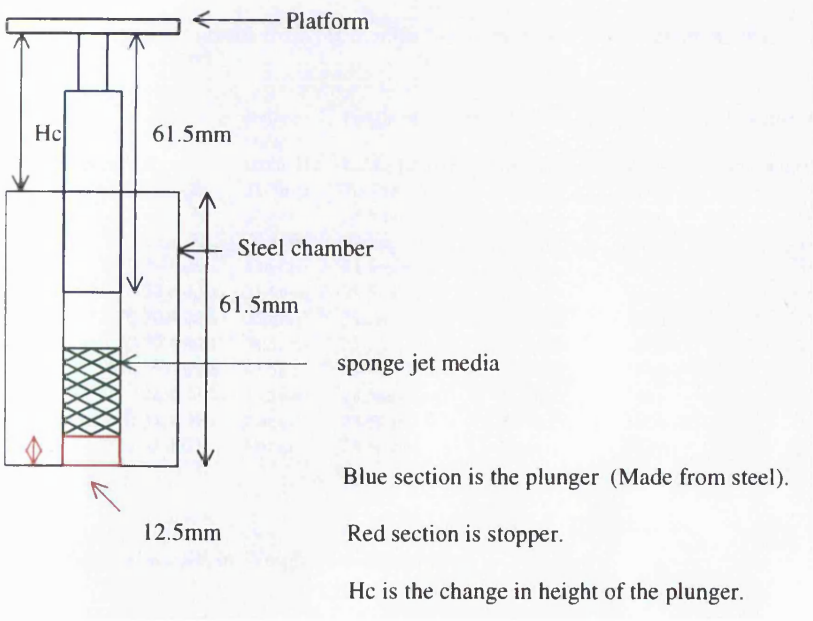


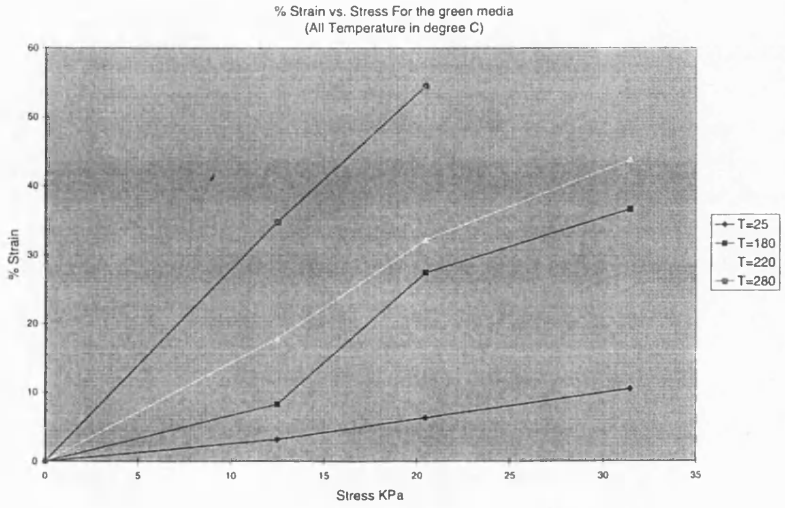
FIGURE 4.2n: COMPRESSION TEST RIG FOR MEASUREMENT OF SPONGE PROPERTIES UNDER LOADING AT TEMPERATURE

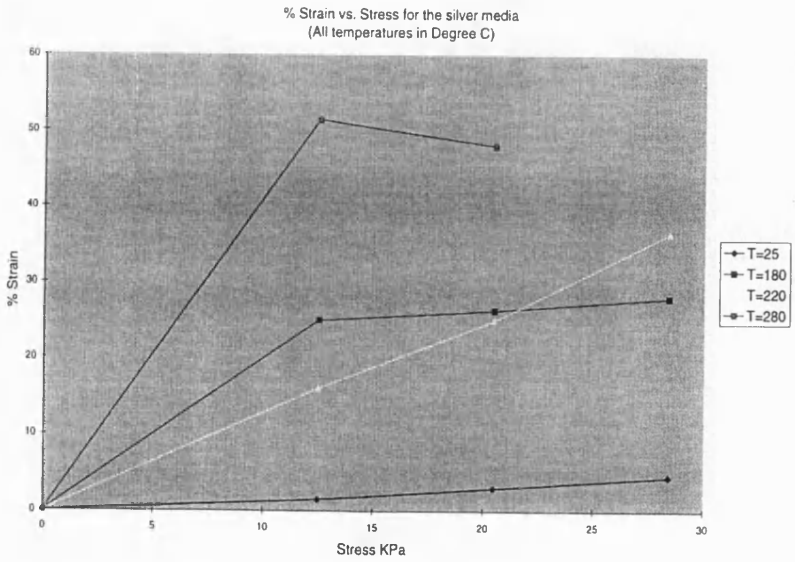


Trials were conducted by loading the chamber separately with Green and Silver media and measuring deflection with loading and change in temperature were recorded. Figure

4.2o shows the change in percentage strain with increasing stress for both Green and Silver media respectively, at fixed temperatures.

FIGURE 4.2o: GRAPHS OF PERCENTAGE STRAIN AGAINST STRESS





Green medium deforms relatively consistently in that the strain increases fairly uniformly with rising stress, the level of strain rises dramatically with temperature. This rise also occurs with Silver medium, except that there is some evidence that strain falls at higher

temperature and stress. This may be a function of the alumina grit particles within the sponge matrix and the thermal breakdown of the sponge itself. Another observation is that the percentage strain for a given stress in Silver medium is less than half that of Green medium at room temperature (25°C), while at higher temperatures there is a similar percentage strain up to approximately 12.5 kPa. Again this may be due to the presence of inflexible grit particles shortening the distances of flexible polyurethane available for deformation (and therefore strain) as measured by deflection of the rig. Figure 4.2p shows the strain against rising temperature for fixed stresses.

FIGURE 4.2p: GRAPHS OF STRAIN AGAINST TEMPERATURE

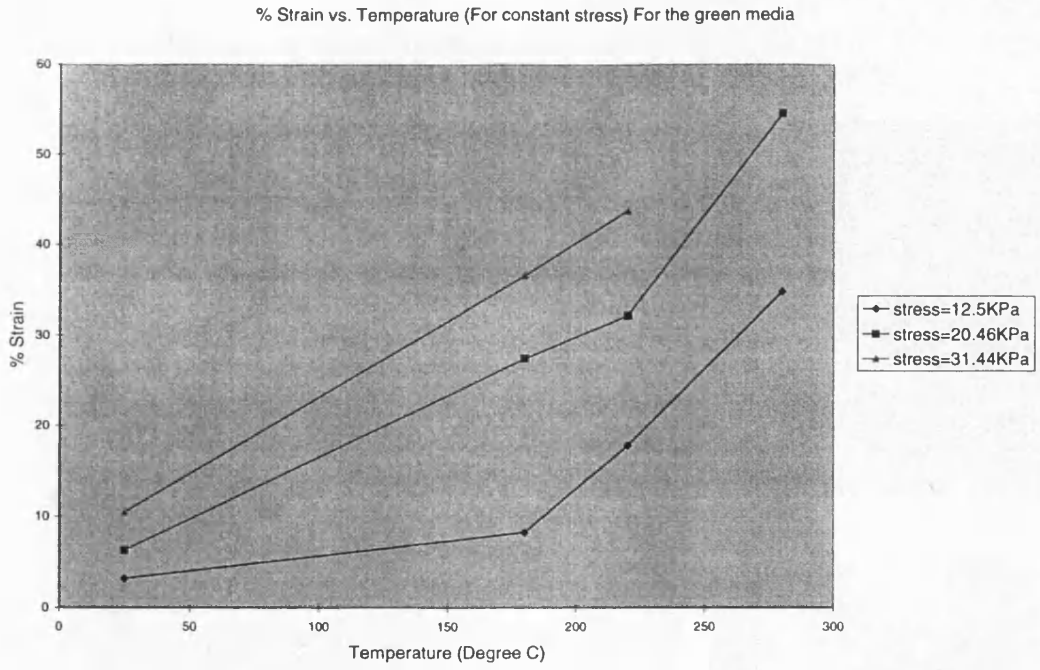
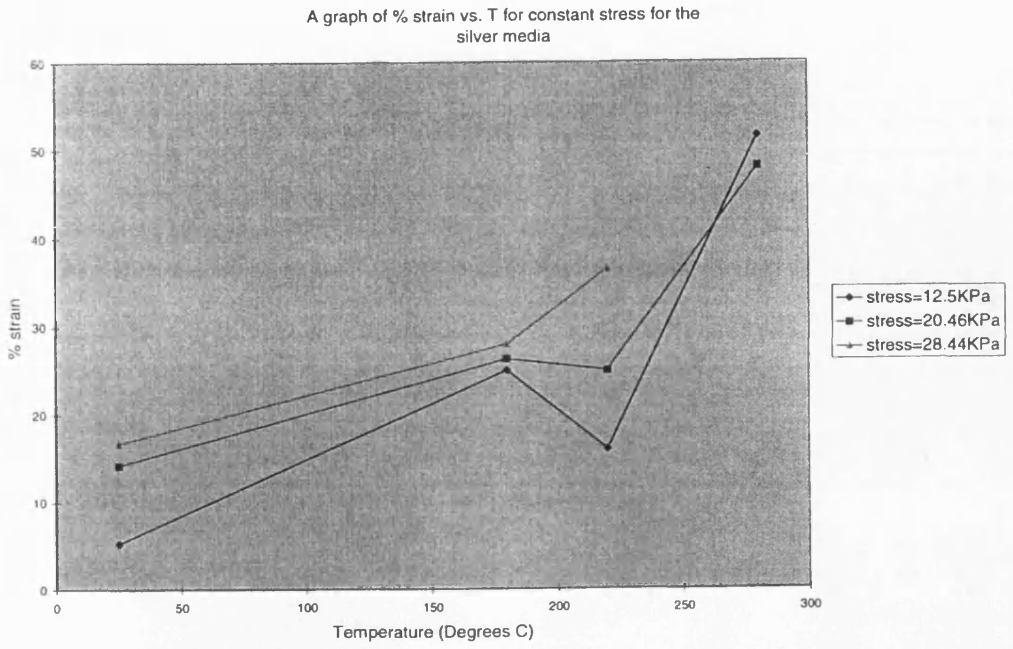
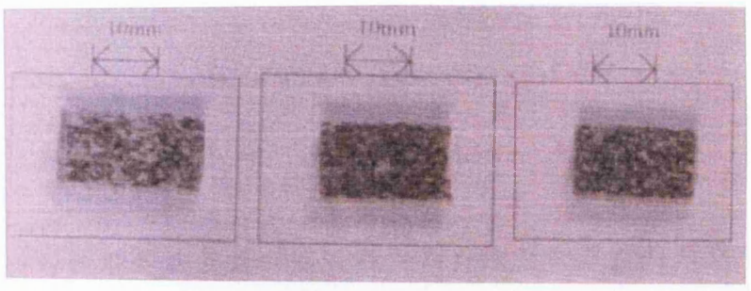


Figure 4.2p. Continued

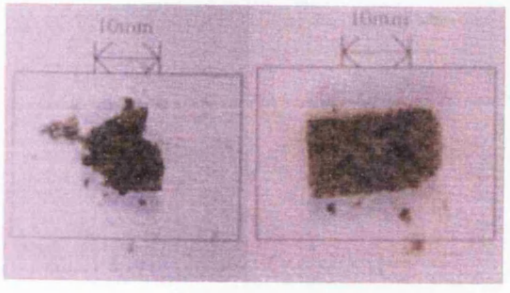


The Green medium exhibits a relatively uniform increase in strain with increasing temperature at each stress level, whereas the Silver medium reveals a drop in strain at temperatures around 220°C. In both cases strain increases relative to the level of stress applied and with increasing temperature. This may suggest some link to the effects shown by the Strain-Stress graphs at fixed temperatures in Figure 4.2o. Clearly the application of heat during compression of the medium will provide a more effective volume reduction. Figure 4.2n shows how trials using the test rig acted as a compression mould generating small pucks of fused medium suggesting the optimum process parameters at ~200-220°C at maximum loading. If this can be scaled up to a feasible operating scale it should produce blocks of compressed sponge medium, which may provide a potentially clean and efficient handling and packaging process for managing the disposal of waste sponge.

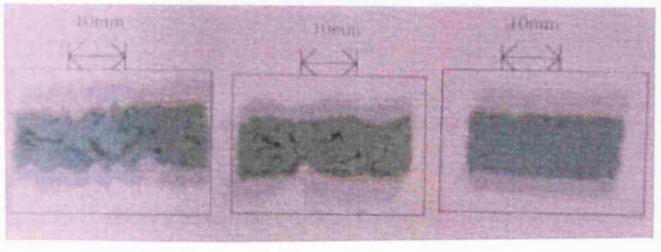
FIGURE 4.2q: VIEWS OF COMPRESSION MOULDED SILVER AND GREEN MEDIA FOLLOWING LOADING AT DIFFERENT TEMPERATURES



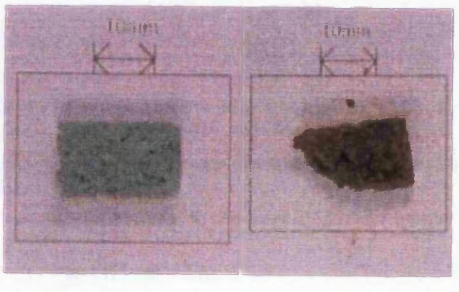
220^0c σ = 12.5kPa 220^0c σ = 20.46kPa 220^0c σ= 31.44kPa



280^0c σ = 12.5kPa 280^0c σ = 20.46kPa



180^0c σ = 12.5kPa 180^0c σ = 20.46kPa 180^0c σ = 28.44kPa



220^0c σ = 31.44kPa 280^0c σ =31.44kPa

Sponge treated surfaces from the milling machine trial and mild steel plates were analysed using a resolved IRS technique (detecting reflected infra-red) to determine whether there were any residual materials left by the process. The technique works in the same way as conventional IRS, except that transmittance is measured following reflectance from a metal surface rather than being measured through transmittance of infra red through the polymer film. Figure 4.2r shows the IRS spectra for a clean metal surface, compared with the machine bed that was treated with the Green medium, and the mild steel plate from the initial trials treated with Silver abrasive medium. This suggests there may be some evidence of residues being left on the surfaces from the Sponge medium. The clean surface (Figure 4.2r (spectra 1)) shows only features related to water and carbon dioxide in the atmosphere at the metal surface. The surfaces following treatment with sponge medium present spectra that have other features reflecting the presence of other material. The second spectra (Figure 4.2r) for the milling machine bed treated with Green non-abrasive medium reveals a loss in transmittance/reflectance around the wavenumber 900 to 1100 cm^{-1}, which if the material present is polyurethane, might reflect the presence of C-N bond stretching [93]. This might not be the case since the medium was only used once and not recycled; there is no abrasion of the surface, and the spectra does not show any other features related to the polyurethane chemical make up. On the other hand there is a great deal of powder material (Wollastonite – see Section 4.1) on the surface of the 'as-new' sponge that may be deposited on to the surface of the metal during the wiping action. This could therefore relate to the presence of $CaSiO_3$ [90]. In contrast to the milling machine surface the abraded metal surface (treated with Silver medium) that would reflect the treated waste surface, a loss in transmittance/reflectance at wavenumbers around 3400 cm^{-1}, and 2900 cm^{-1}, suggesting N-H and C-H bond stretching, respectively [93]. The loss transmittance around 1000 cm^{-1} does not appear to

correlate precisely to the position of a similar loss of transmittance on the milling machine spectra. This further suggests that the feature in the second spectra may be due to something other than polyurethane.

These results suggest that some care will be needed when choosing this process for equipment, whose reuse may be compromised. Although it might be possible to use other grades of non-abrasive media that do not leave residues on the treated surface.

FIGURE 4.2r: IRS SPECTRUM FOR METAL SURFACES TREATED BY THE SPONGE-JET PROCESS
Clean Metal Surface

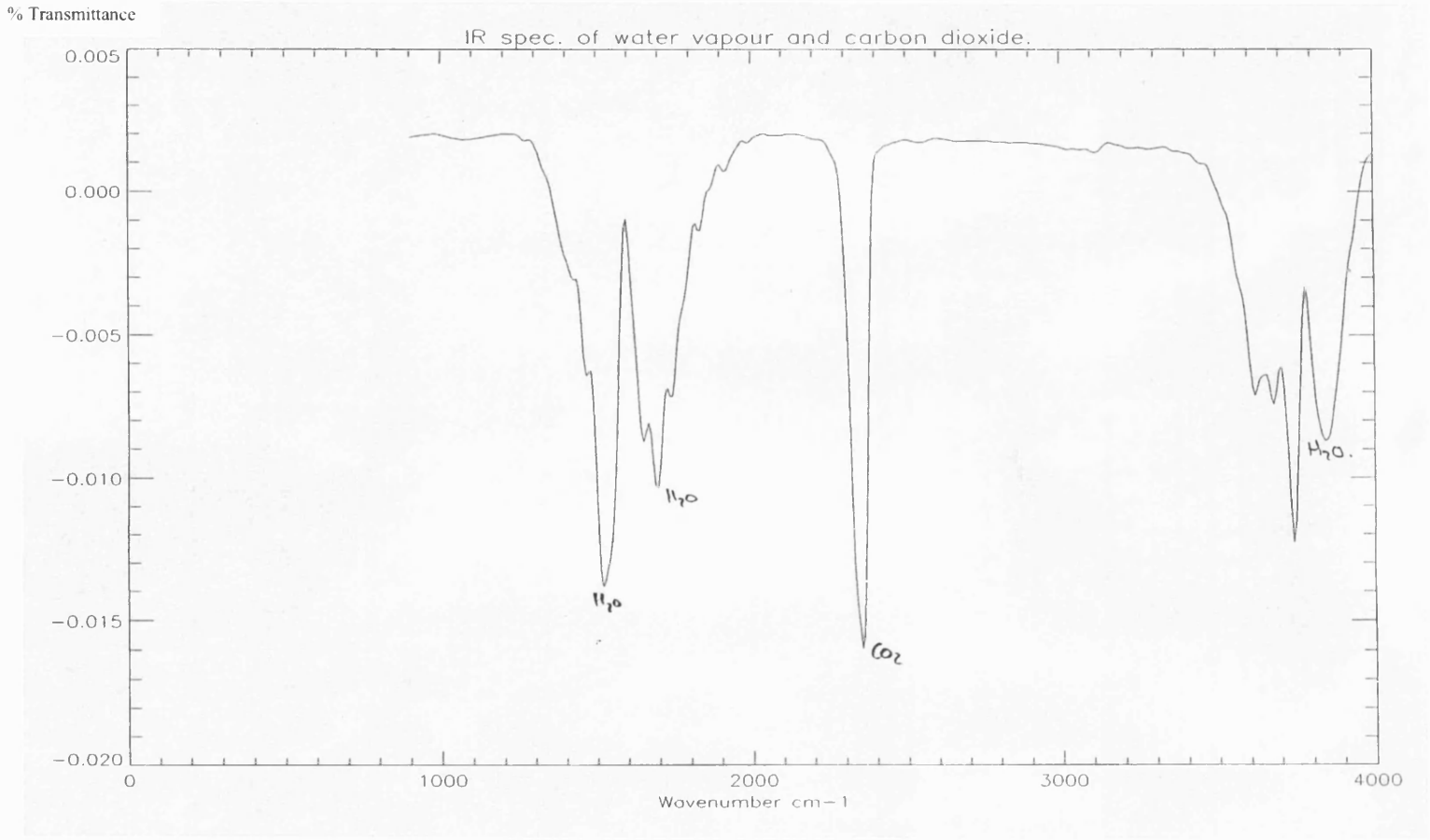


Figure 4.2r. Continued
Milling machine Bed Treated with Green Non-abrasive Medium

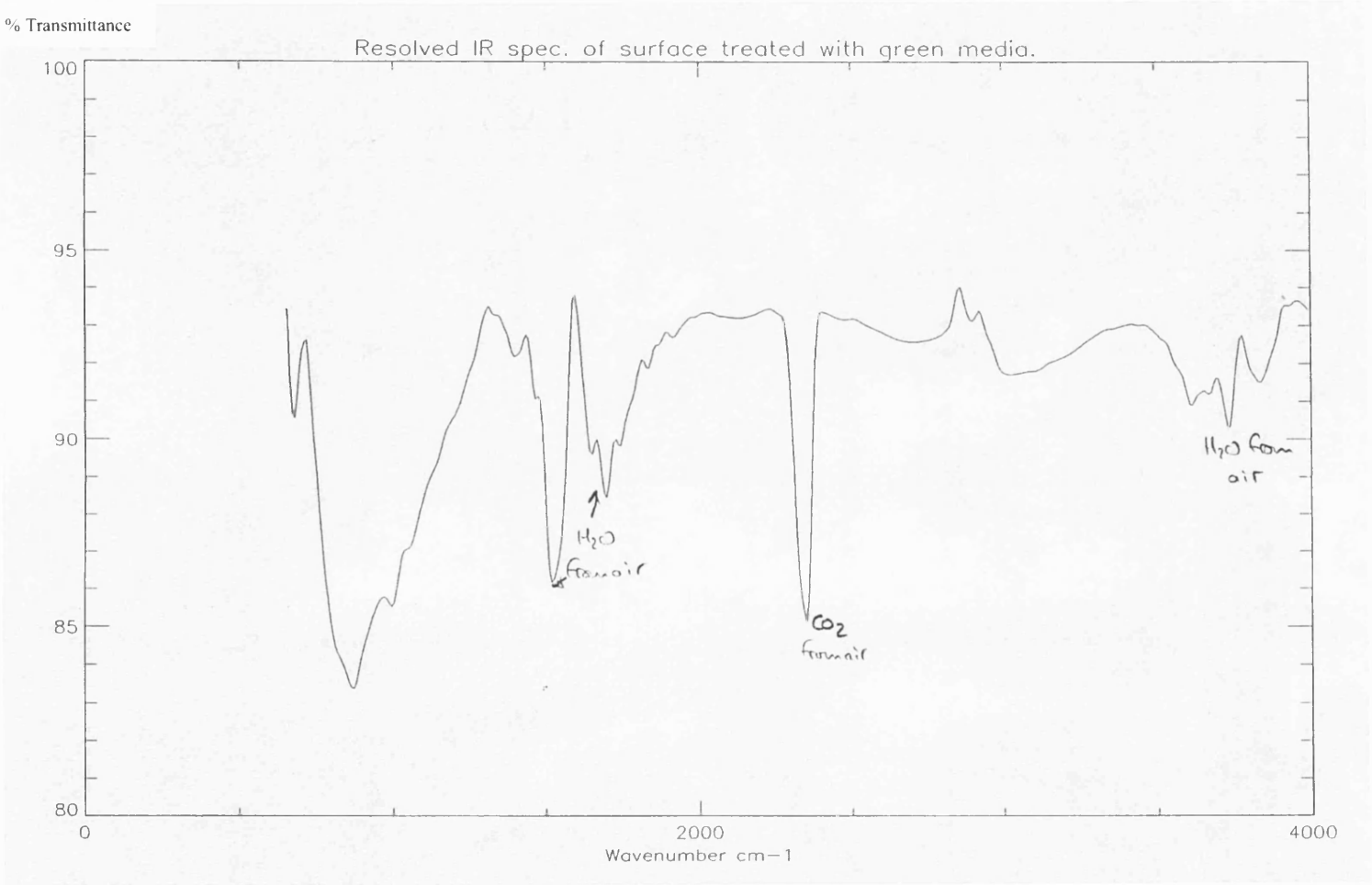
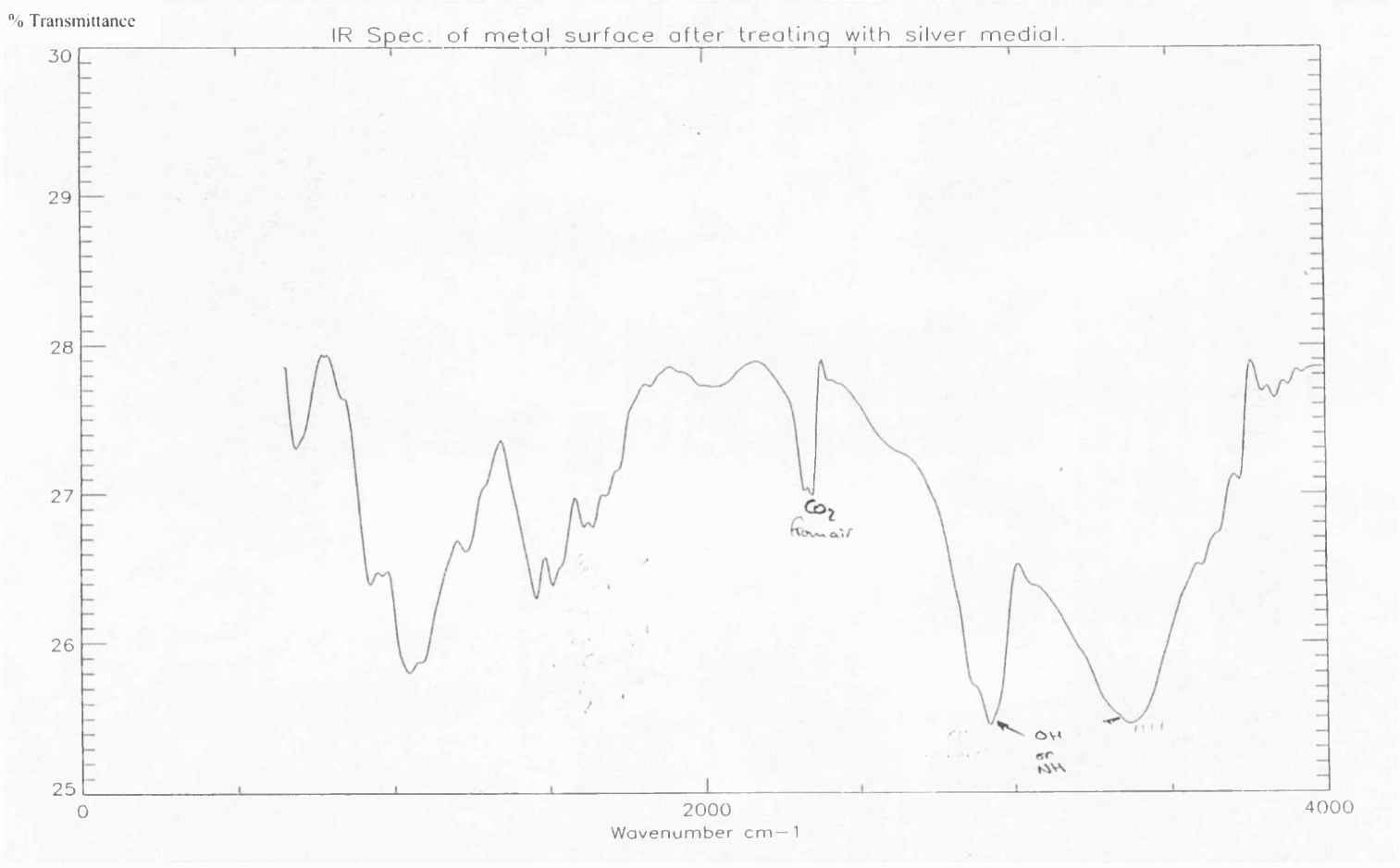


Figure 4.2r. Continued
Mild Steel Plate Treated with Silver Abrasive Medium



4.3 HIGHER ACTIVITY TRIAL RESULTS

Following the LLW trials the need to develop the media management side of the process became apparent to save processing time and make the technology more economically viable due to the smaller savings that are potentially available. Also, in order to use the technology on more active, higher radiation waste, within the WAHF, an automated and remotely operable media management system would need to be developed. As described in Section 3.3 a conceptual system design to contain the blast air and manage the media was proposed. The fundamental design objective of this process would be to enable the media to be recycled, by separating the reusable media and spent fines from the air flow so they may be pneumatically returned for blasting or directed for waste disposal, respectively.

The conceptual design proposes three sets of abatement equipment that will aim to remove the reusable medium, spent medium fines/contaminants and any very fine contamination from the final aerial discharge to atmosphere. The items of equipment are a gravity settler, high efficiency cyclone and HEPA filtration. Before any active trials could be sanctioned it was necessary to actually design and build a prototype system and then undertake inactive trials to confirm the practical performance of the process. If successful, proposals would then be made to carry out higher activity trials. This section describes the results of this design and development process, detailing the outputs from the trials conducted.

4.3.1 System Design

The design sizing of the gravity settler and cyclone were made by using data provided by the Sponge-jet suppliers, and the results obtained from the initial trials. This information was used along with some assumptions to model the particle behaviour in the air stream. This is summarised as follows:

Silver medium bulk density = 530 kg m^{-3} (lower bound)

Particle voidage (assumed) = 0.4

Therefore particle density = $\frac{530}{1 - 0.4}$

= 883 kg m^{-3} (upper bound)

Gravity Settler design:

For vertical settling of >1.5mm particles (see Figure 4.3a., and Chapter 4.1, Figure 4.1h),

for ρ_p = 883 kg m^{-3}

V_s = 5 m s^{-1}

for ρ_{pb} = 530 kg m^{-3}

V_s = 3.7 m s^{-1}

Gas flow rate from nozzle is 4.1 m^3 min^{-1}(air).

As a minimum to maintain containment at the blast booth the system flow rate will be assumed to be 8.2 m^3 min^{-1} (i.e. it pulls twice the air delivered from the nozzle).

Duct sizes:

for 15 m s^{-1} at 8.2 m^3 min^{-1}

cross sectional area of the duct = $\frac{8.2}{15 \times 60}$

= 9.1 x 10^{-3} m^2

Therefore the duct diameter = $\sqrt{9.1 \times 10^{-3} \cdot \frac{4}{\pi}}$

= 0.108 m (4.24 inches)

Nominally a 100mm diameter flexible ducting could be used.

Vertical separator size:

$$\text{for} \quad V_s = 3.7 \text{ m s}^{-1} \text{ at } 8.2 \text{ m}^3 \text{ min}^{-1}$$

$$\text{the vessel area} = \frac{8.2}{3.7 \times 60}$$

$$= 0.037 \text{ m}^2$$

Therefore the vessel diameter = 0.217 m (8.5 inches)

So the vessel height, assuming two diameters above the inlet and one diameter below the inlet, will be 0.65 m (plus ends).

If the particle settling velocity (V_s) was as high as 5.0 m s^{-1}.

$$\text{Then the volumetric air flow} = \frac{8.2 \times 5.0}{3.7}$$

$$= 11.08 \text{ m}^3 \text{ min}^{-1}$$

$$\text{Therefore air velocity is} = \frac{11.08}{60 \times \frac{\pi}{4} \times 0.108^2}$$

$$= 20.2 \text{ m s}^{-1}$$

These calculations were confirmed by inputting some of these figures into computer a modelling programme used by an in-house AEA Technology business, Hyprotech, for terminal or settling velocity calculations [94]. Hyprotech (now Aspen) is a trading name for a Thermo-fluid flow modelling software company purchased by AEA Technology in 1997. Figure 4.3a summarises the report from this modelling programme. This suggests that a particle just over 1.5 mm across will settle out of flow at ~3.7 m s^{-1} if its density is similar to the bulk density of the Silver medium as supplied. If particles that are processed are heavier due to contaminants, collapse of pores/cells, or if more dense medium is used

FIGURE 4.3a: TERMINAL VELOCITY CALCULATIONS

Terminal Settling Velocity Calculator

Particle Stokes diameter =	1500 um	Settling velocity =	3.7 m/s
Particle density =	530 kg/m^3		
Gas density =	1.2 kg/m^3		
Gas viscosity =	1.8E-005 N.s/m^2		

Stokes settling (Rep < 1):

Vr = 36.0245 m/s	dp = 480.72105 um
Rep = 3602.45	Rep = 118.57786

Intermediate settling (1 < Rep < 1000):

Rep = 368.80956	Rep = 371.41849
CD = 0.6356307	CD = 0.6339683
Vr = 3.6880956 m/s	dp = 1505.7506 um
New Rep = 368.80956	New Rep = 371.41849

Terminal Velocity = 3.688 m/s **Particle Diameter = 1506 um**

Terminal Settling Velocity Calculator

Particle Stokes diameter =	1500 um	Settling velocity =	5 m/s
Particle density =	883 kg/m^3		
Gas density =	1.2 kg/m^3		
Gas viscosity =	1.8E-005 N.s/m^2		

Stokes settling (Rep < 1):

Vr = 60.072625 m/s	dp = 432.75088 um
Rep = 6007.2625	Rep = 144.25029

Intermediate settling (1 < Rep < 1000):

Rep = 504.23342	Rep = 494.93619
CD = 0.5670542	CD = 0.5708566
Vr = 5.0423342 m/s	dp = 1484.8086 um
New Rep = 504.23342	New Rep = 494.93619

Terminal Velocity = 5.042 m/s **Particle Diameter = 1485 um**

at a later date, flow speeds will need to be increased to avoid the cut size for the gravity settler dropping below 1.5 mm. If this occurs, it is predicted that an increasing proportion of the spent fines will be carried over in to subsequent recycled blasting operations, potentially impeding the decontamination process.

Cyclone design

The design basis for the cyclone assumes a maximum differential pressure ($\delta\rho$) of 2000 Pa at 11.08 m^3 min^{-1}. Since in-cave space is limited the aim is to return the highest efficiency in the most compact design with only one cyclone. It is already known that the Sponge-jet system delivers 23 kg of medium in approximately 7 minutes, and it assumed that the efficiency of the gravity settler is 80%. The dust flow rate is therefore:

$$= (1 - 0.8) \times \frac{23}{7}$$

$$= 0.66 \text{ kg min}^{-1}$$

This represents the 20% losses seen in the initial trials. The density of these finer particles is assumed to be 883 kg m^{-3} (grit or medium with no voidage).

These parameters, and the bounding flow rates of 15 m s^{-1} and 20 m s^{-1} used in the gravity settler design, were then input into a process engineering software tool used by the Separation Process Services arm of Hyprotech, AEA Technology [94]. Figure 4.3b shows the results of these modelling runs for the cyclone design described in Figure 4.3c.

FIGURE 4.3b: CYCLONE DESIGN REPORTS FOR THE RANGE OF FLOW RATES EXPECTED FOR THE MEDIA MANAGEMENT SYSTEM

At lower flow rates

TKRpt01 Thu 03 Sep 1998 12:08 pm

Cyclone Design Results Report

- SPS High Efficiency

Creation information

▶ SPS High Efficiency

- Operating Conditions
- Performance Criteria
- Cyclone Geometry
- Cyclone Performance

▶Operating Conditions

- Inlet gas conditions
- Dust size distribution

○ Inlet gas conditions

- Gas flow

Name	Windscale Abrasive Foam System - Low Flow
Fluctuating flow	No fluctuations
Volumetric flow rate	0.1367 m^3/s
Temperature	20.01 C [293.2 K]
Pressure	101.3 kPa [1.013E5 Pa]
Correlate properties	[Density,Viscosity]

- Gas properties

Density	1.197 kg/m^3
Viscosity	0.01801 cP [1.801E-5 kg/m/s]

- AirMixture

Nitrogen content	79 % [0.79]
Oxygen content	20 % [0.2]
Carbon dioxide content	1 % [0.01]
Humidity	0.01 kg/kg

- Dust flow

Mass flow rate	0.011 kg/s
Solids concentration	80.49 g/m^3 [0.08049 kg/m^3]

Figure 4.3b Continued

- Dust properties

Name	Default foam
Density	530 kg/m^3
Is the dust erosive	[Very]
Is the dust sticky	[No]
Is the dust friable	[No]

Dust size distribution

- Particle distribution

Name	An Example Medium Dust
Source	[Log-probability]
Distribution type	[Percent mass based]

- Particle distribution data

Sample description	Log-probability type distribution
Density	530 kg/m^3
Shape factor coefficient A1	1
Shape factor coefficient A2	0 um^-1 [0 m^-1]
Shape factor coefficient A3	0 um^-2 [0 m^-2]
Type of size	Aerodynamic
Measuring instrument	Generated by PSDEdit
Operator	N/A
Reference	17/02/1997
Comment	None

- Entered distribution data
  - Log probability particle distribution

Mean diameter	20 um [2E-5 m]
Standard deviation	3

  - Particle size distribution data

Figure 4.3b Continued

Performance results

Name	SPS High Efficiency
Result	[Fail]
Inlet velocity	13.26 m/s
Number of cyclones	1
Overall efficiency	93.44 %
Loading corrected overall efficiency	96.63 %
Cut diameter	3.459 um [3.459E-6 m]
Empirical pressure drop	1095 Pa
Theoretical pressure drop	1090 Pa
Pressure drop reduction, %	33.39
Hopper required	Hopper required
Seals required	Seals required
Vortex breaker required	Required
Check cone erosion	Erosion likely; check cone

Theoretical pressure drop calculation method = Muschelknautz theoretical model

Cyclone grade efficiency curve

	Particle diameter	Grade efficiency
	um	%
1	1.012	0
2	1.472	5.2
3	2.116	15.7
4	3.033	40.2
5	4.349	70.5
6	6.232	91.8
7	9.049	99.3
8	13.08	100

Grade efficiency calculation method = SPS geometry independent scaling

Figure 4.3b Continued
Higher flow rate calculation

TKRpt01 Thu 03 Sep 1998 12:05 pm

Cyclone Design Results Report

- SPS High Efficiency

Creation information

▶ SPS High Efficiency

- Operating Conditions
- Performance Criteria
- Cyclone Geometry
- Cyclone Performance

▶Operating Conditions

- Inlet gas conditions
- Dust size distribution

○ Inlet gas conditions

- Gas flow

Name	Windscale Abrasive Foam System
Fluctuating flow	No fluctuations
Volumetric flow rate	0.1847 m^3/s
Temperature	20.01 C [293.2 K]
Pressure	101.3 kPa [1.013E5 Pa]
Correlate properties	[Density,Viscosity]

  - Gas properties

Density	1.197 kg/m^3
Viscosity	0.01801 cP [1.801E-5 kg/m/s]

- AirMixture

Nitrogen content	79 % [0.79]
Oxygen content	20 % [0.2]
Carbon dioxide content	1 % [0.01]
Humidity	0.01 kg/kg

- Dust flow

Mass flow rate	0.011 kg/s
Solids concentration	59.57 g/m^3 [0.05957 kg/m^3]

Figure 4.3b Continued

- Dust properties

Name	Default foam
Density	883 kg/m^3
Is the dust erosive	[Very]
Is the dust sticky	[No]
Is the dust friable	[No]

Dust size distribution

- Particle distribution

Name	An Example Medium Dust
Source	[Log-probability]
Distribution type	[Percent mass based]

- Particle distribution data

Sample description	Log-probability type distribution
Density	883 kg/m^3
Shape factor coefficient A1	1
Shape factor coefficient A2	0 um^-1 [0 m^-1]
Shape factor coefficient A3	0 um^-2 [0 m^-2]
Type of size	Aerodynamic
Measuring instrument	Generated by PSDEdit
Operator	N/A
Reference	17/02/1997
Comment	None

- Entered distribution data
  - Log probability particle distribution

Mean diameter	20 um [2E-5 m]
Standard deviation	3

  - Particle size distribution data

Figure 4.3b Continued

▶Performance Criteria

Name	Default
Number of cyclones	1
Inlet velocity	0 m/s
Overall efficiency	0 %
Pressure drop	2 kPa [2000 Pa]
Sharpness of cut range	[]
Cut diameter source	Calculated
Cut diameter	0 um [0 m]

▶Cyclone Geometry

Name	SPS High Efficiency
Barrel diameter	0.3175 m
Vortex finder diameter	0.1319 m
Vortex finder length	0.2074 m
Overall height	1.111 m
Barrel height	0.4763 m
Inlet height	0.1623 m
Inlet width	0.0635 m
Dust exit diameter	0.1334 m
Inlet type	[Tangential]
Mean inlet diameter	0.254 m
Axial inlet vane angle	0 Degree [0 Radian]

Figure 4.3b Continued

Performance results

Name	SPS High Efficiency
Result	[Fail]
Inlet velocity	17.92 m/s
Number of cyclones	1
Overall efficiency	96.91 %
Loading corrected overall efficiency	98.32 %
Cut diameter	2.255 um [2.255E-6 m]
Empirical pressure drop	2000 Pa
Theoretical pressure drop	2052 Pa
Pressure drop reduction, %	27.87
Hopper required	Hopper required
Seals required	Seals required
Vortex breaker required	Required
Check cone erosion	Erosion likely; check cone

Theoretical pressure drop calculation method = Muschelknautz theoretical model

Cyclone grade efficiency curve

	Particle diameter	Grade efficiency
	um	%
1	0.6597	0
2	0.9596	5.2
3	1.379	15.7
4	1.978	40.2
5	2.835	70.5
6	4.063	91.8
7	5.9	99.3
8	8.528	100

Grade efficiency calculation method = SPS geometry independent scaling

The modelling software outputs suggest that the capture efficiency of the cyclone design in Figure 4.3c will start falling from a particle size of around 10 μm. At the lower air velocity of 15 m s^{-1} the efficiency starts to fall for particles of ~13 μm, while at the higher air velocity of 20 m s^{-1} the cyclone is predicted to be 100% efficient for particles down to ~8.5 μm in size. If the gravity settler is effective for the larger particles it is likely that the smaller particles will be of a higher density than the general bulk density of the medium particles. It is expected that the particles carried over from the gravity settler will be small bits of polyurethane, pieces of alumina grit, and contaminants removed from the blast surface. In most cases it was expected these particles will be larger than 10 μm, but SEM examinations (presented in Chapter 4.2, following this design and inactive commissioning work) show that there are a significant number of particles in the medium of <10 μm in size. Large amounts of sub-micron particles such as aerosols are not expected. Some of these particles may not be abated by the cyclone, and remain in the air stream to be captured by the HEPA filter. While this may be problematic in terms of filter life and consequent additional waste volumes, if radioactive particles pass the cyclone the filter life expectancy will diminish more rapidly, since replacement will be based on disposal cost for radioactivity and not filter pressure drop or failure. This notwithstanding it is expected that most radioactive contaminants will be much more dense than the Sponge-jet media material and may be expected to have a higher probability of capture by the cyclone. This suggests that the management system should be run at higher volumetric air flow than the assumed flow rate of 8.2 m^3 min^{-1}. Commissioning trials will cover the range from 8 to 12 m^3 min^{-1}, but the higher activity trials will need to address the possibility of finer radioactive contaminant carry over to the HEPA filter. Figure 4.3d describes the system design and Figure 4.3e shows the system installed in an inactive cave mock-up facility.

FIGURE 4.3c: DIMENSIONAL DRAWING OF THE CYCLONE

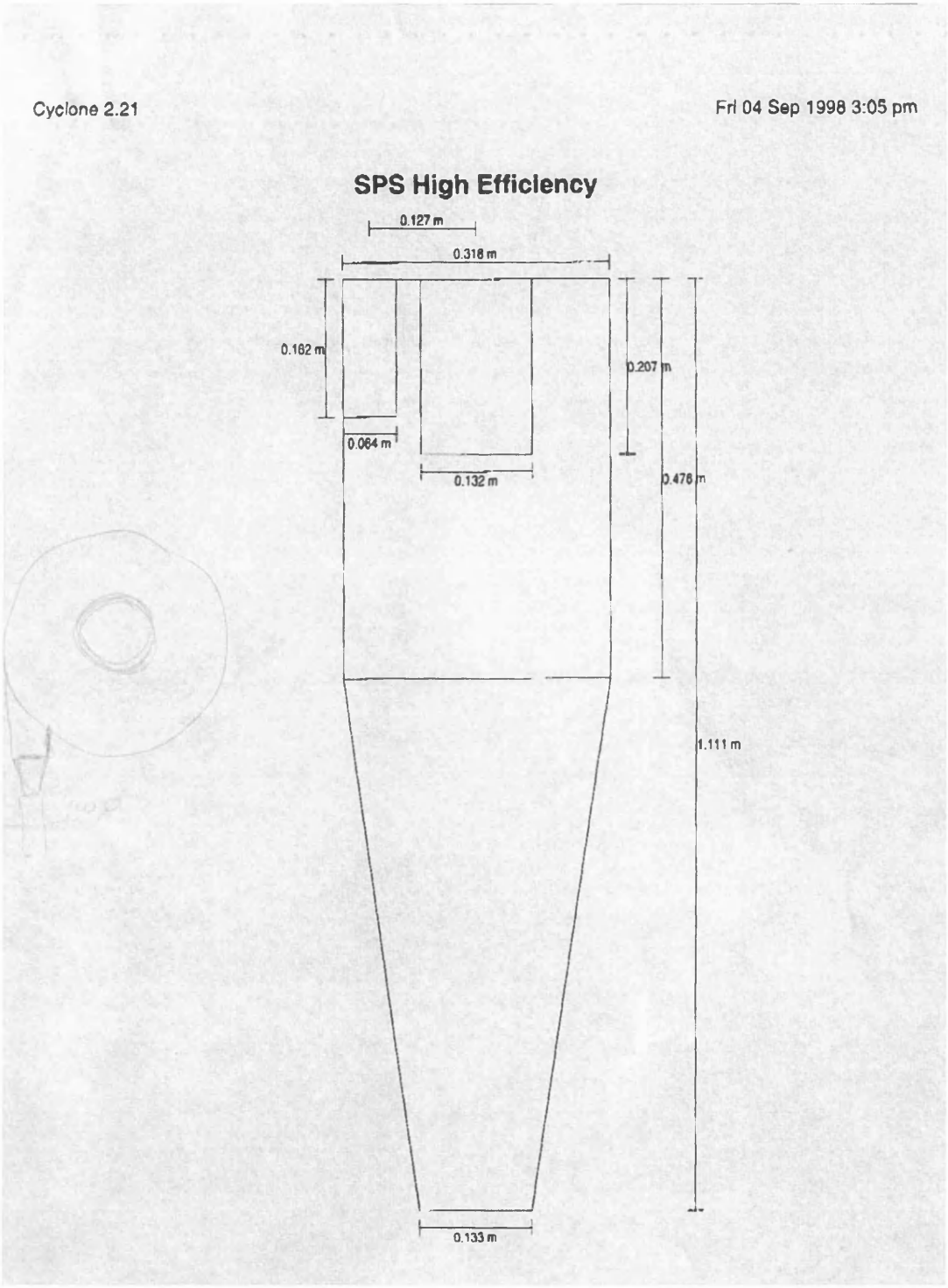
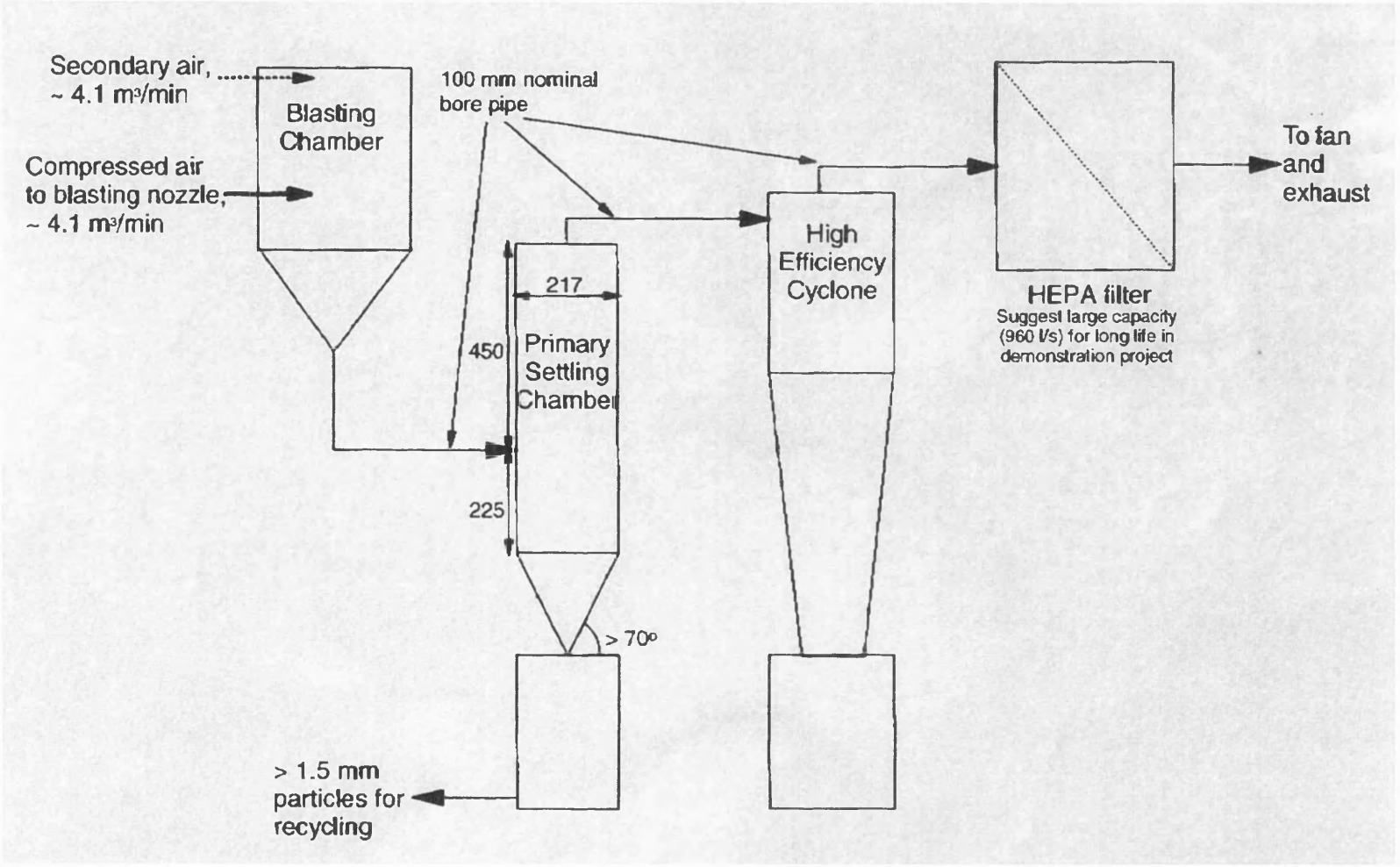


FIGURE 4.3d: SCHEMATIC DRAWING DESCRIBING THE DESIGNED SYSTEM



4.3.2 Inactive Mock-up Commissioning Trials

The gravity settler and cyclone shells were manufactured to design and installed on sliding clamps to mock-up cave bench as shown in Figure 4.3e. The sliding clamp enabled the removal and refitting of collection bins below each collector. The mock-up cave fan was utilised to provide the depression needed to obtain the design flow rates through the system. The cave fan is capable of running at 38 m^3 min^{-1}, and a controller was therefore installed to reduce the flows and control them within the range required by the design. The filter housing required modification to fit a manifold that would enable 100mm diameter flexible hosing to be attached. This hosing was used to connect the filter to the cyclone, the cyclone to the gravity settler, and finally the gravity settler to the blast booth hopper. The blast booth hopper conveniently fitted in the flask liner well enabling the blast booth to sit at a height that allowed remote viewing and operation through the mock-up cave window. A cross frame was installed inside the hopper to support a 1.5 r.p.m. motor that would rotate a steel specimen attached to a turntable, backward and forward, in front of a tilting blast nozzle. The blast nozzle penetrated through the side-wall of the blast booth. The nozzle was attached to a support that facilitated grip and manipulation by an MSM to direct the blast jet in a tilt and panning action covering all areas of the waste specimen as it rotates on the turntable. The blast boot itself was ~1 m^3, fitted with two toughened glass viewing windows. A gap around the blast nozzle access was made large enough to allow air ingress to the booth, but hopefully small enough to ensure flow rates prevent medium bouncing out of the booth.

FIGURE 4.3e: THE PROTOTYPE HIGHER ACTIVITY DECONTAMINATION SYSTEM SET UP FOR INACTIVE COMMISSIONING TRIALS

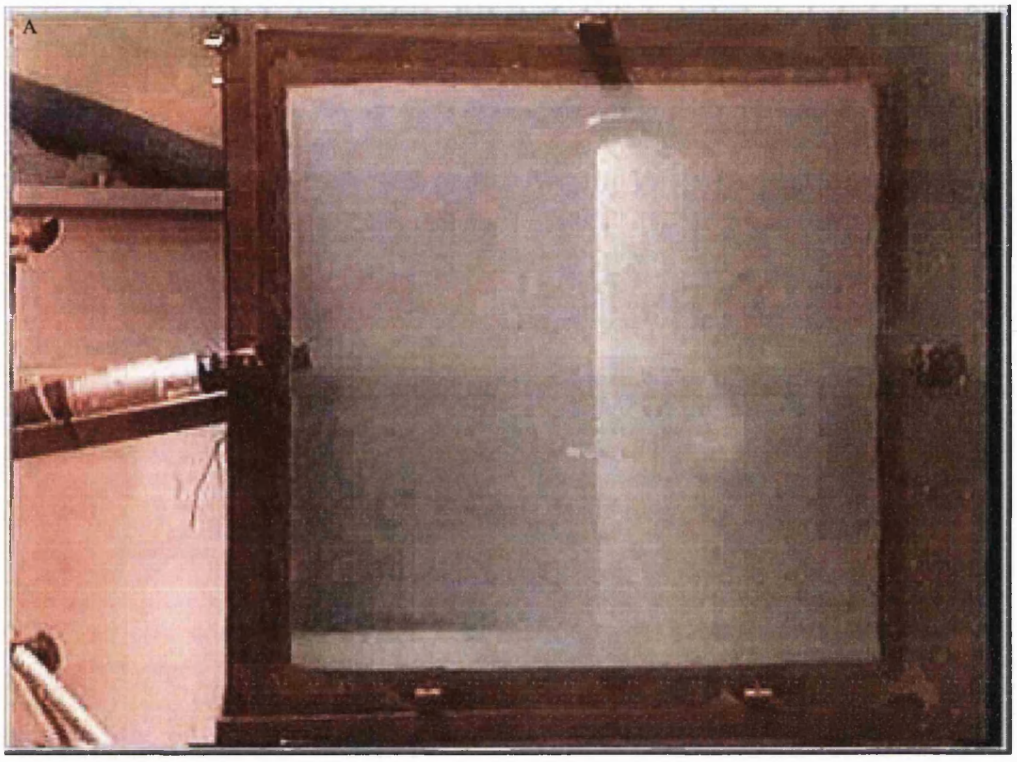
View along the inside of the mock-up cave with blast booth, gravity settler and cyclone (from left to right)

View with blast booth hood removed to show rotary table and specimen supported on a frame within the hopper. The exhaust pulls from the bottom of the hopper via the blue flexible hosing connected to the settler, cyclone, filters, fan to atmosphere.

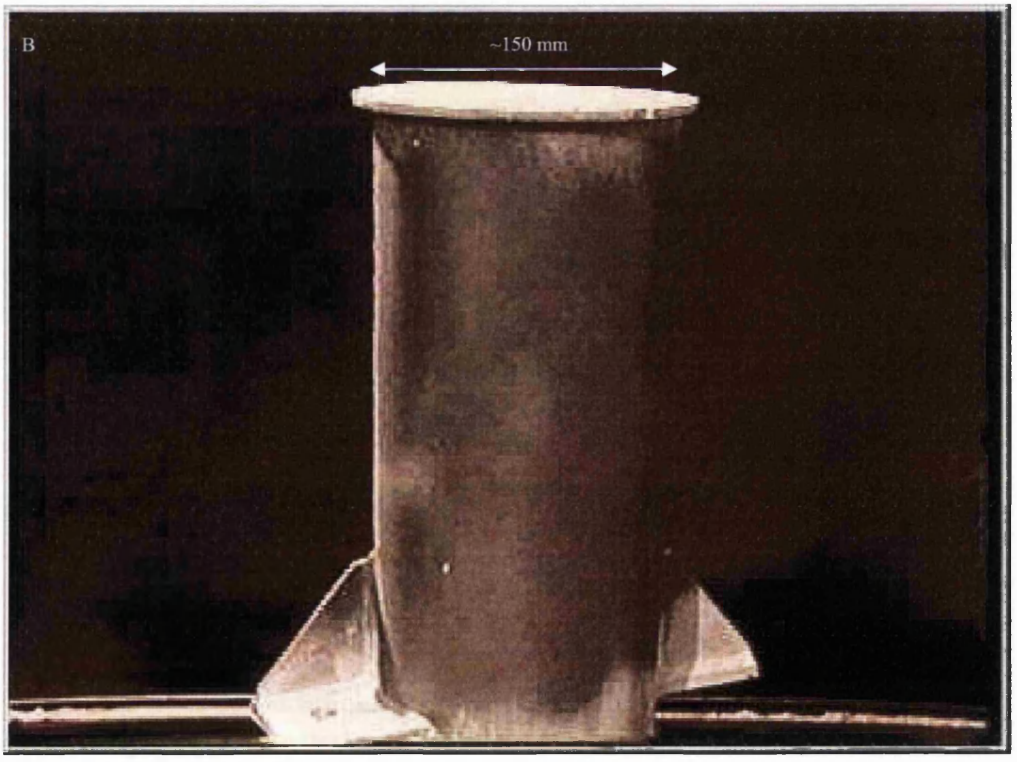
The fan speed controller was calibrated against the in duct air speed using a hot-wire anemometer. In case there were any differences in the running of the system with the fan operating at the same speed with different blast pressures, measurements were taken at blast pressures from 30 psi to 70 psi, but no variations in duct air flows prior to the gravity settler and cyclone were detected. It was therefore possible to focus the recycling trials on collections at different blast pressures (30, 50 and 70 psi), using three in-duct air speeds (14, 18 and 22 m s^{-1}). The steel vessel used as a trial waste specimen was painted with an acrylic paint to simulate a relatively tenacious contaminated corrosion layer. The trial charge of medium for recycling was limited to the collector bin volume ~11 litres (10993 cm^3). This volume of medium was blasted at the painted steel vessel five times for each blast pressure and flow rate, and the losses measured. The collector bin was filled to a ~30 cm depth for the start of each trial. Since the collector bin was 21.6 cm in diameter, each centimetre of reusable medium equates to approximately 366 cm^3. It is recognised that this is not strictly true since the medium particles may pack more closely as they break down, and the depth of collected fines was not proportionate. Nevertheless this does provide a measure of the system performance against the design and for comparison against the manual grading system as described in Chapter 4.1. Figure 4.3f shows the results of blasting the steel vessel with these small charges of medium.

Table 4.3a and Figure 4.3g summarise the measurements of medium losses at different blasting pressures and system duct flows. Losses range from just over 11% at the lower blast pressure and system flow rates (30 psi and 14 m s^{-2}) to just over 17% at the higher flow rates (70 psi and 22 m s^{-1}) per pass. This compares favourably with the manual grading method trial where losses of ~20% were measured. Some medium dust was collected after each trial from the corrugated ducting, but no medium fines were observed

FIGURE 4.3f: PAINT BEING REMOVED FROM COMMISSIONING TRIAL SPECIMEN

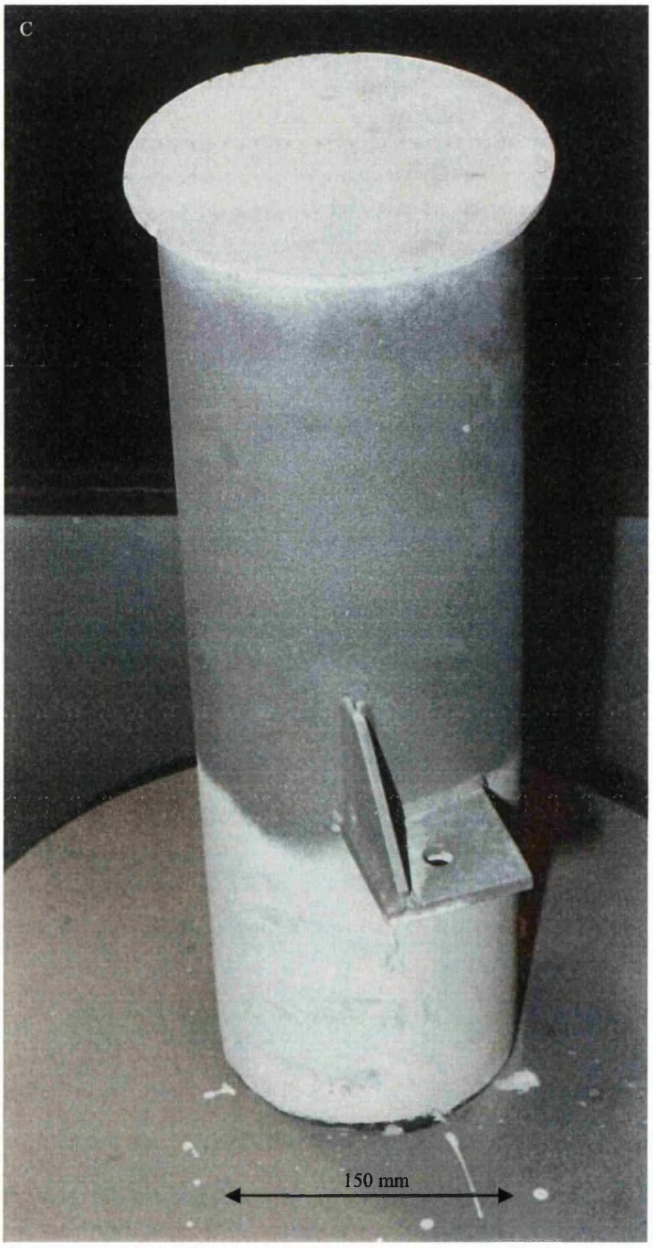


View from cave face showing the blast nozzle being deployed remotely through side of blast booth at rotating trial specimen



View of simulated waste item after sponge-jet blasting showing how paint coating has been removed

Figure 4.3f. Continued



Plates C, D and E show how the abrasive cutting effect of Sponge-jet not only removes the surface layer but can clean awkward angles and clean up welds

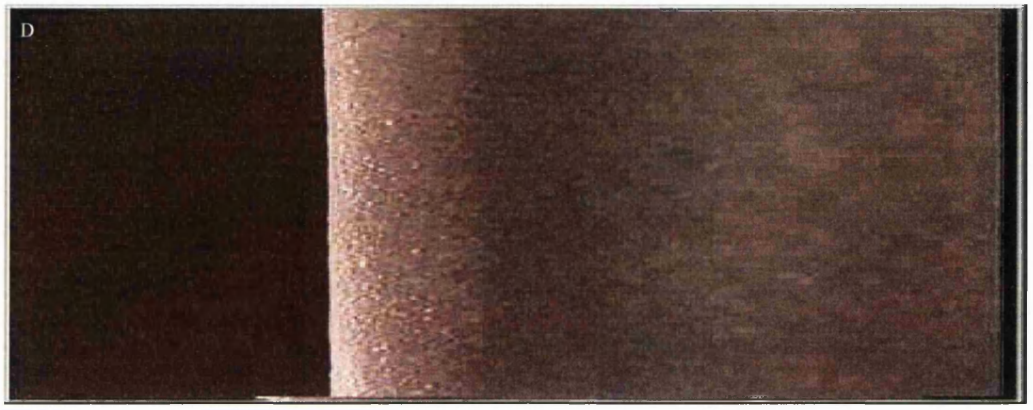
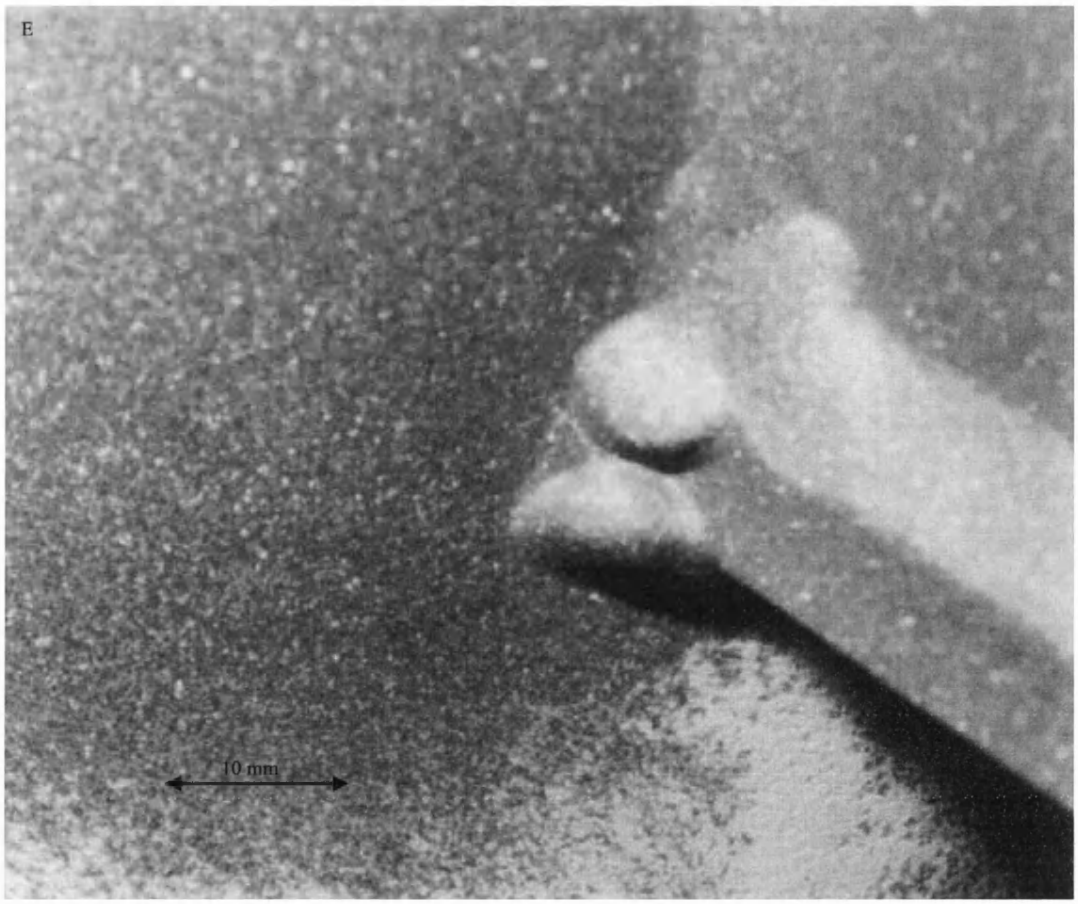


Figure 4.3f: Continued



in the ducting from the cyclone to the filter. Indeed the filters were removed and tamped onto a plastic sheet and no particles were visible. The original weight of each charge of medium was measured to be nominally 5.3 kg and the weight of all medium from system after the blast trial was 5.92 kg. This represents a ~12% increase in weight, whereas the initial inactive trials measured a ~9% increase. Since the initial trials were on bare metal and these trials were cleaning a painted surface the difference may be due to the weight of paint particles.

Figure 4.3h shows clearly the difference in the particle size collected by the gravity settler and the cyclone. On the basis of these results it was possible to move to higher

TABLE 4.3a: GRAVITY SETTLER COLLECTION LOSSES DURING MOCK-UP TRIALS

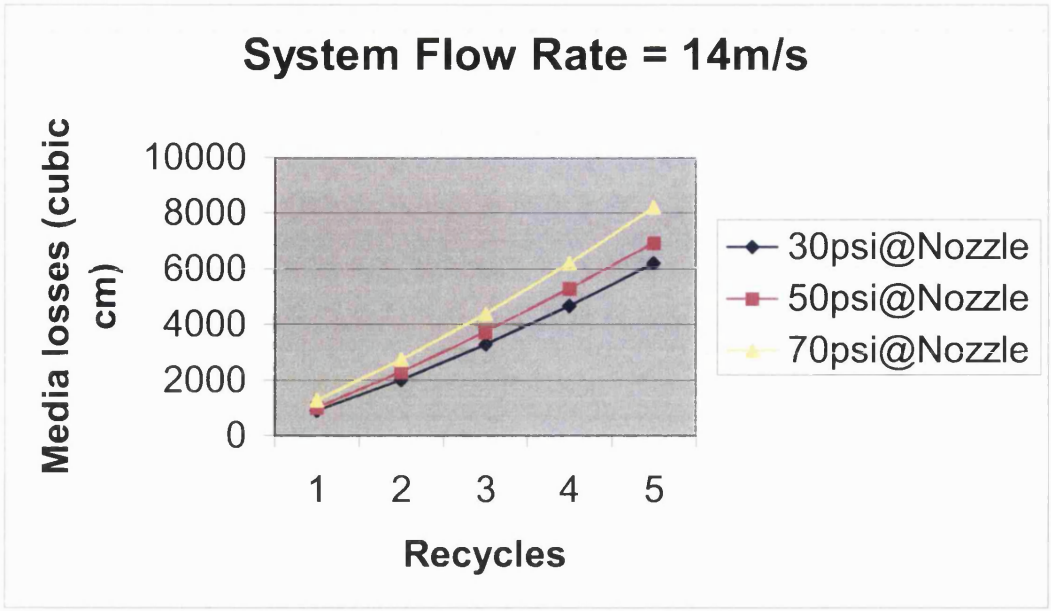
Blast Pressure (psi)	Duct Flow (m/s)	PASSES*					Total Loss (cm)	Mean Loss per Pass (cm)	% Loss per pass**
		1	2	3	4	5			
30	14	2.50	3.00	3.50	3.75	4.25	17.00	3.40	11.3
	18	2.75	3.25	4.00	4.25	4.50	18.75	3.75	12.5
	22	3.25	3.75	4.25	4.75	5.25	21.25	4.25	14.2
50	14	2.75	3.50	4.00	4.25	4.50	19.00	3.80	12.7
	18	3.50	4.00	4.50	4.50	4.75	21.25	4.25	14.2
	22	4.00	4.50	4.75	5.00	5.00	23.25	4.65	15.5
70	14	3.50	4.00	4.50	5.00	5.50	22.50	4.50	15.0
	18	3.75	4.25	4.75	5.25	5.75	23.75	4.75	15.8
	22	4.25	4.75	5.25	5.50	6.00***	26.00	5.20	17.3

* Measurements could only be made at +/- 0.25 cm, or +/- 91.5 cm^3, which is equivalent to just over +/- 1% of the original charge. Errors in measurement were minimised as far as possible by tamping the tins to get a level settling of the medium prior to each measurement.

** Starting charge was 30 cm of medium (~10993 cm^3), where 1cm = ~366 cm^3.

*** This was estimated because there was so little medium left it was difficult to measure level medium.

FIGURE 4.3g: GRAPHS COMPARING LOSSES AT DIFFERENT FLOW RATES AND BLAST PRESSURES



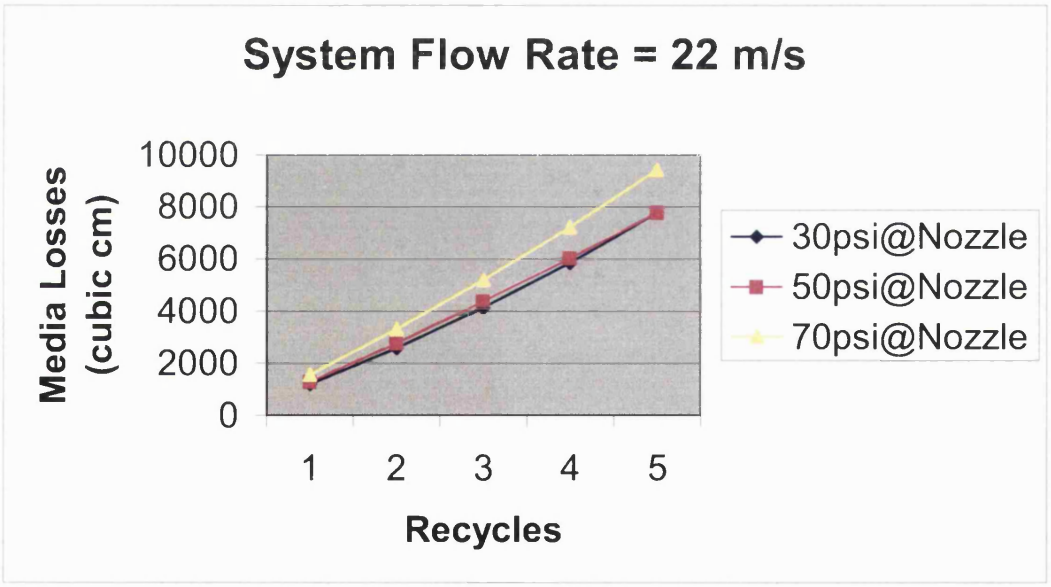
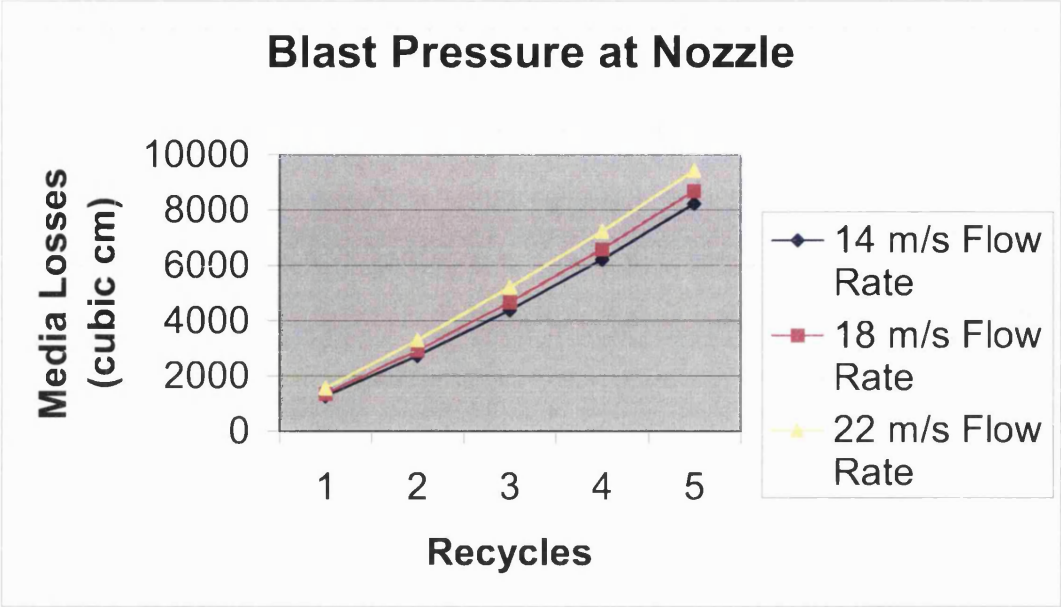


Figure 4.3g Continued



activity waste decontamination trials. This system was dismantled and taken to the WAHF for installation in the LLW enclosure as described in Chapter 3.3.

4.3.3 Higher Activity Trial Results

A number of steel tools used in-cave for uranium fuel de-cladding operations were retrieved for higher activity decontamination trials. Figure 4.3i shows the results of monitoring surveys on these tools. There are four die inserts, two die blocks and four handling tools from a press. The four die inserts could be used as a controlled trial using

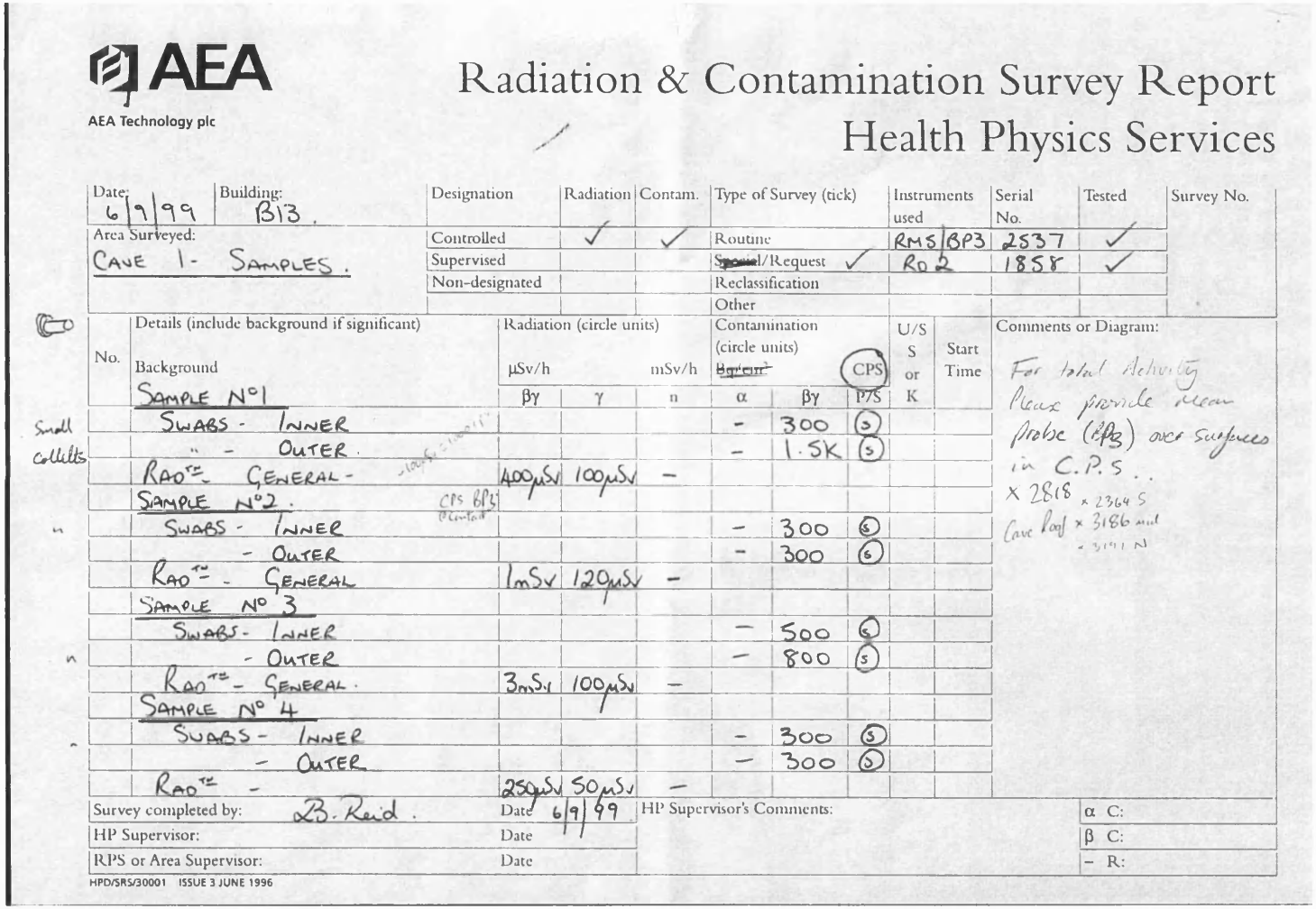
FIGURE 4.3h: MEDIA CAPTURE FROM THE GRAVITY SETTLER AND CYCLONE

Gravity Settler Collection

Figure 4.3h. Continued

High Efficiency Cyclone Collection

FIGURE 4.3i: MONITORING REPORTS FOR CONTAMINATED ITEMS OF WASTE TO BE USED IN THE HIGHER ACTIVITY TRIALS



AEA Technology plc

Radiation & Contamination Survey Report
Health Physics Services

Date: 6/9/99	Building: B13.	Designation	Radiation	Contam.	Type of Survey (tick)	Instruments used	Serial No.	Tested	Survey No.
Area Surveyed: CAVE 1 - SAMPLES.		Controlled	✓	✓	Routine	RMS BP3	2537	✓	
		Supervised			~~Special~~/Request ✓	RO 2	1858	✓	
		Non-designated			Reclassification				
					Other				

No.	Details (include background if significant) Background	Radiation (circle units) µSv/h βγ	γ	mSv/h n	Contamination (circle units) ~~Bq/cm²~~ α	CPS βγ	P/S	U/S S or K	Start Time	Comments or Diagram:
	SAMPLE N°1									For total Activity Please provide mean probe (CPS) over surfaces in C.P.S..
small collets	SWABS - INNER				-	300	(S)			
	" - OUTER				-	1.5K	(S)			
	RAD TECH - GENERAL -	400µSv	100µSv	-						
	SAMPLE N°2. CPS BP3 Contact									
"	SWABS - INNER				-	300	(S)			
	- OUTER				-	300	(S)			
	RAD TECH - GENERAL	1mSv	120µSv	-						
	SAMPLE N° 3									
	SWABS - INNER				-	500	(S)			
"	- OUTER				-	800	(S)			
	RAD TECH - GENERAL.	3mSv	100µSv	-						
	SAMPLE N° 4									
	SWABS - INNER				-	300	(S)			
	- OUTER				-	300	(S)			
	RAD TECH -	250µSv	50µSv	-						

Survey completed by: B. Reid.	Date 6/9/99	HP Supervisor's Comments:	α C:
HP Supervisor:	Date		β C:
RPS or Area Supervisor:	Date		- R:

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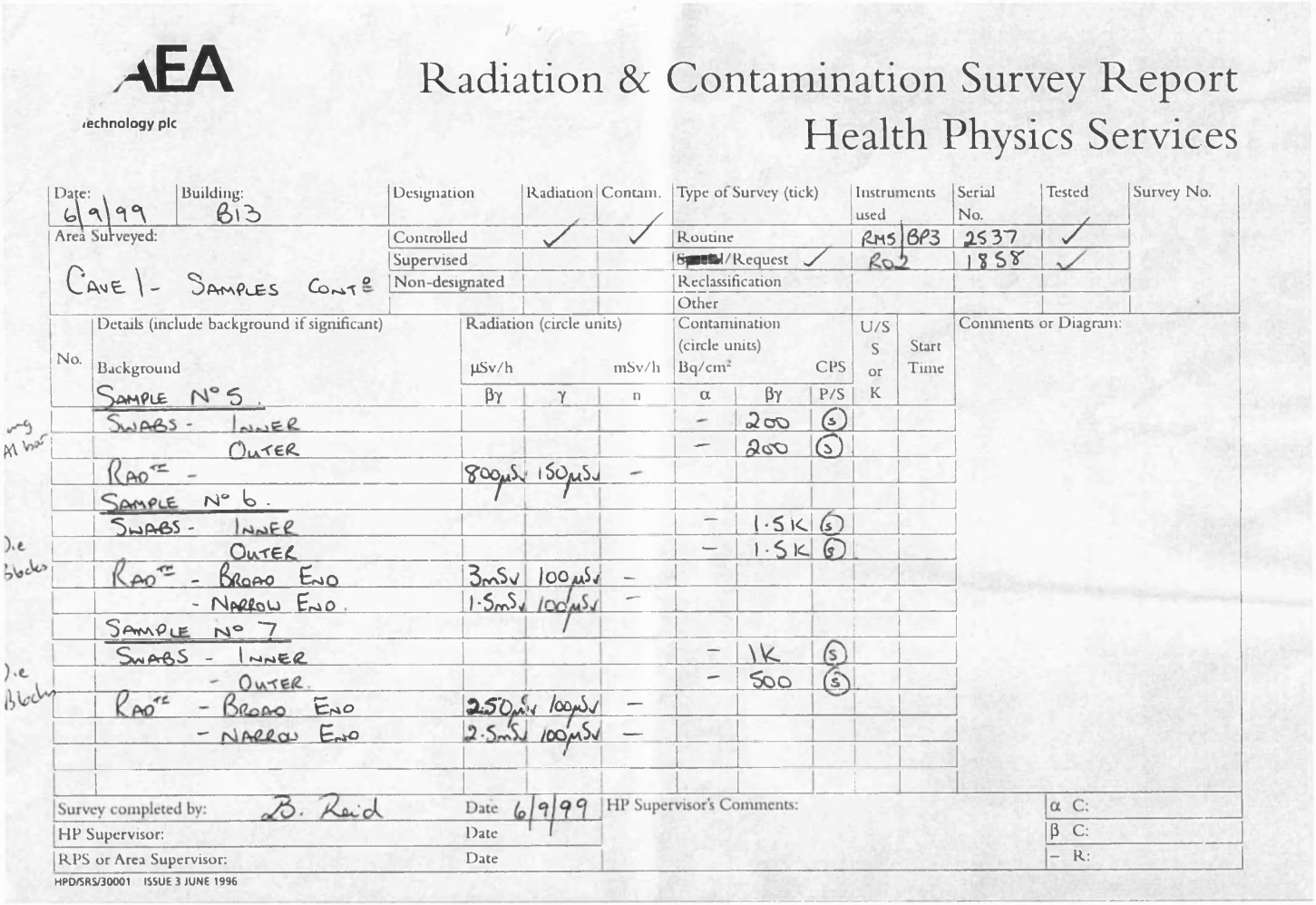
Figure 4.3i. Continued



AEA technology plc

Radiation & Contamination Survey Report
Health Physics Services

Date:	Building:	Designation	Radiation	Contam.	Type of Survey (tick)	Instruments used	Serial No.	Tested	Survey No.
6/9/99	B13	Controlled	✓	✓	Routine	RMS / BP3	2537	✓	
Area Surveyed:		Supervised			[redacted]/Request ✓	RO2	1858	✓	
CAVE 1 - SAMPLES CONTD		Non-designated			Reclassification				
					Other				

No.	Details (include background if significant) Background	Radiation (circle units) µSv/h βγ	γ	mSv/h n	Contamination (circle units) Bq/cm² α	βγ	CPS P/S	U/S S or K	Start Time	Comments or Diagram:
	SAMPLE N° 5.									
	SWABS - INNER				-	200	(S)			
	OUTER				-	200	(S)			
	RAD^{TE} -	800µSv	150µSv	-						
	SAMPLE N° 6.									
	SWABS - INNER				-	1·5K	(S)			
	OUTER				-	1·5K	(S)			
	RAD^{TE} - BROAD END	3mSv	100µSv	-						
	- NARROW END.	1·5mSv	100µSv	-						
	SAMPLE N° 7									
	SWABS - INNER				-	1K	(S)			
	- OUTER.				-	500	(S)			
	RAD^{TE} - BROAD END	250µSv	100µSv	-						
	- NARROW END	2·5mSv	100µSv	-						

Survey completed by: B. Reid	Date 6/9/99	HP Supervisor's Comments:	α C:
HP Supervisor:	Date		β C:
RPS or Area Supervisor:	Date		– R:

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Figure 4.3i. Continued

AEA Technology plc

Radiation & Contamination Survey Report
Health Physics Services

Date:	Building:	Designation	Radiation	Contam.	Type of Survey (tick)	Instruments used	Serial No.	Tested	Survey No.
6/9/99	B13.	Controlled	✓	✓	Routine	RMS/BP3	2537	✓	
Area Surveyed:		Supervised			Special/Request ✓	RO2	1858	✓	
CAVE 1 - SAMPLES CONT^D		Non-designated			Reclassification				
					Other				

No.	Details (include background if significant) Background	Radiation (circle units) µSv/h βγ	µSv/h γ	mSv/h n	Contamination (circle units) Bq/cm² α	Bq/cm² βγ	CPS P/S	U/S S or K	Start Time	Comments or Diagram:
	SAMPLE N° 8									
Tools	SWABS - INNER				-	200	(S)			
	- OUTER				-	3K	(S)			
	RAD^{TN} - GENERAL	2mSv	120µSv	-						
	SAMPLE N° 9.									
Tools	SWABS -				-	200	(S)			
	RAD^{TN} - GENERAL.	1mSv	150µSv	-						
	SAMPLE N° 10.									
Tools	SWABS -				-	2K	(S)			
	RAD^{TN} GENERAL.	3.5mSv	100µSv	-						

Survey completed by:	Date	HP Supervisor's Comments:	α C:
HP Supervisor:	Date		β C:
RPS or Area Supervisor:	Date		- R:

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a single charge of silver medium (~18.7 ltr). Their radiation levels range from 250 μSv hr^{-1} βγ (sample 4) to 3 mSv hr^{-1} βγ (sample 3). The other samples (samples 5 to 10 on Figure 4.3i) would be held in reserve pending the results of decontaminating these first four die insert specimens. The four die inserts are effectively tubes ~10 cm long with a bore diameter of just over 2.54 cm and a shoulder at one end. They have exactly the same surface area (4 x 0.0187 m^2), which is small enough to be cleaned by the medium that is limited to the charge size of the collector bins. It was possible to obtain larger collector bins (25 cm dia. x 38 cm deep) and adapt the system on installation. Another modification had to be made to take account of the height of the blast booth and hopper. There was no flask liner well in which to stand them and this led to the hopper being truncated and the ducting pulling off to the side. Radiation measurements and samples were taken in a number of ways during the trial in order to try and understand the way radioactive contamination is transferred throughout the system.

Table 4.3b summarises the radiological monitoring data taken from the samples and system during these higher activity trials. Actual samples of medium and fines can be taken and measured in the Scaler. Swabs can be taken of loose contamination taken from the inner surfaces of the system. The specimens are assumed to have both fixed and non-fixed contamination present, so the RO2 radiation dose rate meter measurements were used and converted to radioactivity (Bq/specimen) using conversion tables (see Figure 2.5a). The activity removed from the specimens can be represented by,

Specimen Activity (before) (Bq cm^{-2} x Surface Area) _____ Specimen Activity (after) (Bq cm^{-2} x Surface Area)

Where, ~100 μSv hr^{-1} ≈ 1000 c.p.s.
and ~ 1000 c.p.s. ≈ 800 Bq cm^{-2}
and specimen surface area = 187 cm^2
(for a BP3 probe and βγ contamination)

TABLE 4.3b: HIGHER ACTIVE TRIAL SAMPLE AND SYSTEM MONITORING

Specimen Id.	Contaminated Die Insert RO2 ($\mu Sv\ hr^{-1}\beta\gamma$)	Cleaned die insert RO2 ($\mu Sv\ hr^{-1}\beta\gamma$)	Hopper by Swab[2] (cpm)[2]	Gravity Settler Media (cpm)[3]	Gravity Settler by Swab[2] (cpm)[3]	Cyclone Media (cpm)[3]	Cyclone by Swab[2] (cpm)[3]	Enclosure floor near blast booth (cpm)[3]	α/β in air (whole trial) (cpm)[3]
1	250	15	38	65 - 153	20	364	18	79	
2	400	40	226	780 - 1220	20	1830	115	520	
3	1000	420	1124	1252 - 3172	66	6404	170	550	
4	3000	2200[1] 500[1]	3966[4]	14124 – 16200[4]	115	4633[4]	368	2456	23 α 362 β

(1) Due to a blockage in the hopper there was insufficient medium recycled to clean both sides of the die insert.
(2) Hopper surfaces swabbed on different surfaces after each trial pass, where as the gravity settler and cyclone were swabbed on the same surfaces at the outlets.
(3) The Scalar instrument efficiency is 11.3% (on second shelf) for meduma monitoring, and 24% on first shelf for swab paper sampling.
(4) Modification to the hopper led to blocking in the outlet pipe following slumping, no medium was collected in the gravity settler bin, therefore a sample of medium was taken from the hopper. The cyclone did not appear to have collected any more fines, but another sample was taken.

This permits the radiation monitoring results to be converted to counts per second, activity per unit area, and then because the sample surface area is known (~18 cm^2), total activity per sample in Becquerels. This can be used to assess the total activity removed from all specimens for comparison with the activity estimated to remain on the specimens after the decontamination trial, and contamination transferred elsewhere in the system. Since the other samples are either swabs from contaminated surfaces or samples of sponge meduma, the monitoring results also need to be converted in to radioactivity (Bq) and extrapolated in order to relate to the full internal area of the system, or volume of medium each measurement represents. The swabs and medium samples are measured using the Harwell 6000 Series Scaler Pulse Counter. There are two tray levels in the counting chamber where one is approximately one centimetre further away from the detector than the other leading to lower detection efficiency. The swab papers could be measured on the top tray with an efficiency of 24%, while the second tray was used for the medium were only an 11.3% efficiency is achieved.

Commissioning trials with the system connected to the building main extract duct via the mobile fan-filter unit showed that the arrangement could only achieve a flow rate of 6.4 m^3 min^{-1}, ~80% of the minimum design flow rate. The mobile filtration unit was capable of ~57 m^3 min^{-1} (0.95 m^3 s^{-1}), but this must have been diminished by resistance encountered through delivery to the building main header duct ventilating the whole cave system. These trials went ahead on this basis with the view that it would provide more information on system performance below the flow rates used in the mock-up facility trials, and further trials could be undertaken later once appropriate equipment had been acquired. Nevertheless these compromises appear to have critically influenced the performance of the media management system during the trial. Losses of medium during

the blasting cycles were significantly higher than expected. The modification made to the hopper led to medium collection and eventual slumping, which finally blocked the hopper outlet on the final pass. However an attempt has been made to interpret the results. It was necessary to consider the volumes that were lost on each recycle to make sense of the results. The start charge was a full collector bin (~18650 cm^3) of Silver medium, and only about two thirds of the bin (~12000 cm^3) was available for blasting specimen 2, this reduced to one third of the bin (~6000 cm^3) for specimen 3, while the last specimen was not satisfactorily blasted and is estimated to have seen no more than 3000 cm^3. For the purposes of following the contamination transfer to the system, activity removed from each of the specimens is presented in Table 4.3c.

TABLE 4.3c: CONTAMINATION REMOVAL FROM DIE INSERTS BASED ON ACTIVITY EQUIVALENTS FROM RADIATION MONITORING

Specimen Id.	Est. Pre-Activity (MBq) (1)	Est. Post-Activity (MBq) (1)	Est. Activity Removed (MBq)(2)	Cumulative Activity Removed(MBq)	Decontam. Factor(4)
1	0.37	0.02	0.35	0.35	16.7
2	0.60	0.06	0.54	0.89	10.0
3	1.50	0.63	0.87	1.76(3)	2.4
4	4.49	4.04(5)	0.45	2.21	1.4

(1) From dose rate measurements in Figure 4.3h and Table 4.3b, where 100 $\mu Sv\ hr^{-1} \approx 800\ Bq\ cm^{-2}$, and surface area of the specimen is 187 cm^2.

(2) Subtract estimated post-trial activity from pre-trial activity of the die inserts.

(3) Cumulative activity removed from specimens 1, 2 and 3, is 1.76 MBq, and a decreasing proportion of medium actually went through the system.

(4) Decontamination factor (Df) is the pre-activity divided by the post-activity. Total Df is 1.7, but up to specimen 3 the overall Df is 3.58.

(5) Only one side of insert blasted, dose on one side 2.2 $mSv.hr^{-1}$, while the other was 0.5$mSv.^{-1}$

The activity measurements were made in the Scaler instrument on ~20cm^3 samples of medium that had passed through system and collected in the bins after the first three recycles. The mean measurements for the gravity settler were 109 cpm, 1000 cpm, and 2212 cpm, for pass 1, 2 and 3, respectively (see Table 4.3b). After pass 4 the medium

samples were from the hopper only since the system blocked. The activity for the medium in the gravity settler can be calculated as follows:

$$\text{Activity in GS Media} = \frac{(\text{Sample measurement in cpm} / 60)}{\text{Scaler Efficiency}} \times \frac{\text{Media Vol. in cm}^3}{\text{Sample Vol. in cm}^3} \text{ (Bq)}$$

Therefore the activity in the processed media following each pass is,

Media from sample 1 $\Rightarrow$ 9646 Bq

Media from sample 2 $\Rightarrow$ 44249 Bq

Media from sample 3 $\Rightarrow$ 48938 Bq

These values only represent between 2 and 5% of the estimated activity removed, and even if scaled up to take account of all the media used at each stage (multiply by start media vol./collected media vol.) this would only account for 4%, 16% and 17% of the activity removed at each stage.

The activity in the cyclone medium was collected into volumes of fines after each pass that was estimated to be 600 cm^3 after pass 1, 300 cm^3 after pass 2, and 150 cm^3 after pass 3. The activity collected as a proportion of the total removed can be calculated in the same way as the gravity settler, giving rise to the following figures,

Fines from sample 1 $\Rightarrow$ 1611 Bq 0.5%

Fines from sample 2 $\Rightarrow$ 4049 Bq 0.5%

Fines from sample 3 $\Rightarrow$ 7084 Bq 2.5%

Again if these figures were scaled up to take account of medium that did not go through the system the proportion of activity held in the fines would only rise to 0.7%, 1.4% and 2.5%, respectively for each pass.

The medium retention in the hopper was unexpected, and of the ~3000 cm^3 blasted at specimen 4, none went through to the gravity settler or cyclone. No medium was found in the collector bin below the gravity settler. While the level of fines in the cyclone collector bin did not rise, a sample of fines which was taken off the top of the fines already in the bin, showed a marked increase in activity. Assessment of the hopper medium could only be based on sampling after specimen 4 was blasted. Unlike the gravity settler and cyclone medium the activity in the hopper may be less homogenous throughout the medium. It is likely that the majority of the activity retained in the hopper after each blasting stage lay in the medium that settled in the hopper during that pass. Therefore the final sampling of the hopper could be said to only represent the contamination removed during the blasting of specimen 4, and a likewise case could be made for each previous specimen. The mean activity value for the hopper medium following specimen 4 blasting could be estimated as follows,

$$\frac{(15162/60)}{0.113} \times \frac{3000}{20} = 326767 \text{ Bq}$$

This represents approximately 73% of the estimated activity removed from specimen 4. For the purposes of this activity balance it is assumed that a similar proportion of the activity was held up in medium volumes retained following blasting of the first three specimens. The activity retained by the hopper would therefore be as follows;

Specimen 1 $\Rightarrow$ 0.35 MBq x 0.73 $\Rightarrow$ 0.26 MBq

Specimen 2 $\Rightarrow$ 0.54 MBq x 0.73 $\Rightarrow$ 0.39 MBq

Specimen 3 $\Rightarrow$ 0.87 MBq x 0.73 $\Rightarrow$ 0.64 MBq

Specimen 4 $\Rightarrow$ 0.45 MBq x 0.73 $\Rightarrow$ 0.33 MBq

This would mean that the total activity in the hopper would be in the region of 1.62 MBq. If this is added to the accumulated gravity settler medium and cyclone fines activity (0.095 MBq and 0.013 MBq), the total activity accounted for is 1.64 MBq. This leaves ~0.57 MBq unaccounted for in the system, or either the conversion from dose rate to activity for the specimens is pessimistic, or this extrapolation of the medium and fines activity is an under estimate.

At this stage an attempt was made to assess plate out of activity on the inner surfaces of the system. Using the swab data and known dimensions of the system components the following estimations were made.

For the system upstream of the gravity settler;

Areas	Booth	~5 m^2
	Hopper	~2 m^2
	Duct	~0.7 m^2
	Total	~7.7 m^2
Swabs	Pass 1	38 cpm
	Pass 2	226 cpm
	Pass 3	1124 cpm
	Pass 4	3966 cpm (N.B Blockage)
Scaler efficiency		24%
Swab area		~300 cm^2

$$\text{Activity plated out} = \frac{\text{cpm}/60}{\text{Scaler Eff'y}} \times \frac{\text{Total Area}}{\text{Sample Area}}$$

Activity plated out, Pass 1	~677 Bq
Pass 2	~4028 Bq

Pass 3 ~20034 Bq

Pass 4 ~70690 Bq

This represents approximately 3.2% of the total activity removed, but takes no account of the swab efficiency in removing activity. It is possible that the dry filter paper swabs collect as little as 20% of the activity from a surface, so the plate out could be as high as ~16%, assuming the plate out of activity is fairly uniform. This plate out could account for another 0.35 MBq of activity removed from the specimens. The smaller area of the system down stream of the gravity settler inlet exhibited much less plate out judging from the swab activities alone, although the smaller sample area (outlet necks at collector bins) and the worst case swab could account for ~1-2% of the estimated activity removed from the specimens in the lower part of the system.

Table 4.3d summarises this contamination/radioactivity transfer balance, where nearly 90% of the activity could be accounted for if the assumptions used here are correct. It was also noted from the monitoring surveys that some contamination was on the floor and in the air outside the blasting system within the enclosure which could be as much as 5 to 6% of the activity removed from the specimens; it is more likely to have arisen during the booth handling and specimen loading operations between blasting operations. There is also the possibility that the results from medium samples when monitored could be under estimated due to contaminants being held under, or in the medium leading to a self-shielding effect that is not fully detected.

TABLE 4.3d: CORRECTED ACTIVITY TRANSFER DATA FOR THE HIGHER ACTIVITY TRIALS

Estimated Radioactivity Content of Specimens, Medium and System (MBq)									Percentage (%)
Spec.Id.	Spec. Pre	Spec. Post	Act'yRemoved	Hopper Media	Plateout to GS	GS Media	Cycl. Fines	Plate out after GS	Act'y Accounted
1	0.374	0.022	0.352	0.257	0.001	0.01	0.002	0.0001	77
2	0.598	0.06	0.539	0.393	0.004	0.044	0.004	0.0006	83
3	1.496	0.628	0.868	0.634	0.02	0.049	0.007	0.001	82
4	4.488	4.039	0.449	0.328	0.071			0.002	89
Totals	6.956	4.749	2.208	1.612	0.096	0.103	0.013	0.0037	83

FIGURE 4.3j: ESTIMATED ACTIVITY OF SPECIMENS BEFORE AND AFTER TRIAL

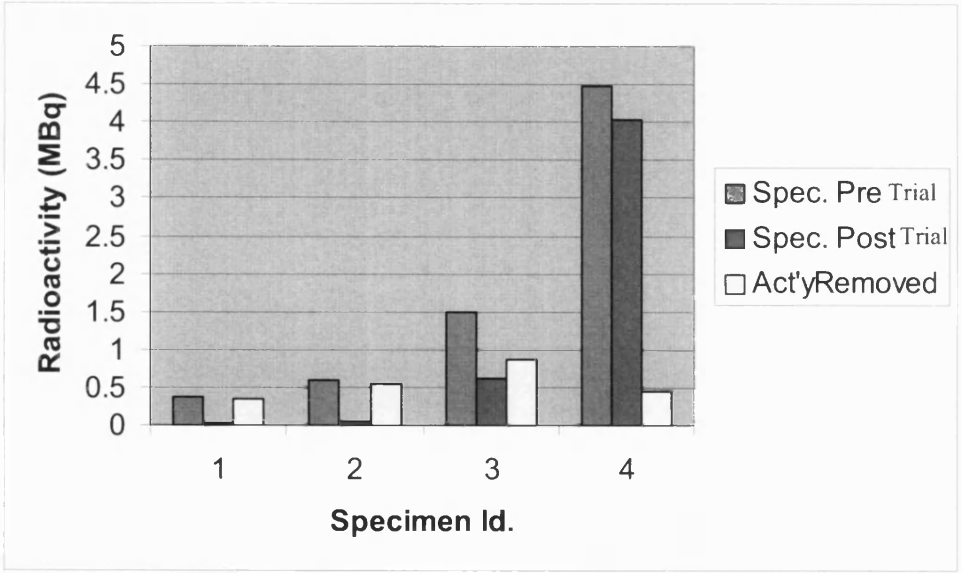


FIGURE 4.3k: ESTIMATED RADIOACTIVITY TRANSFER THROUGH THE PROCESS

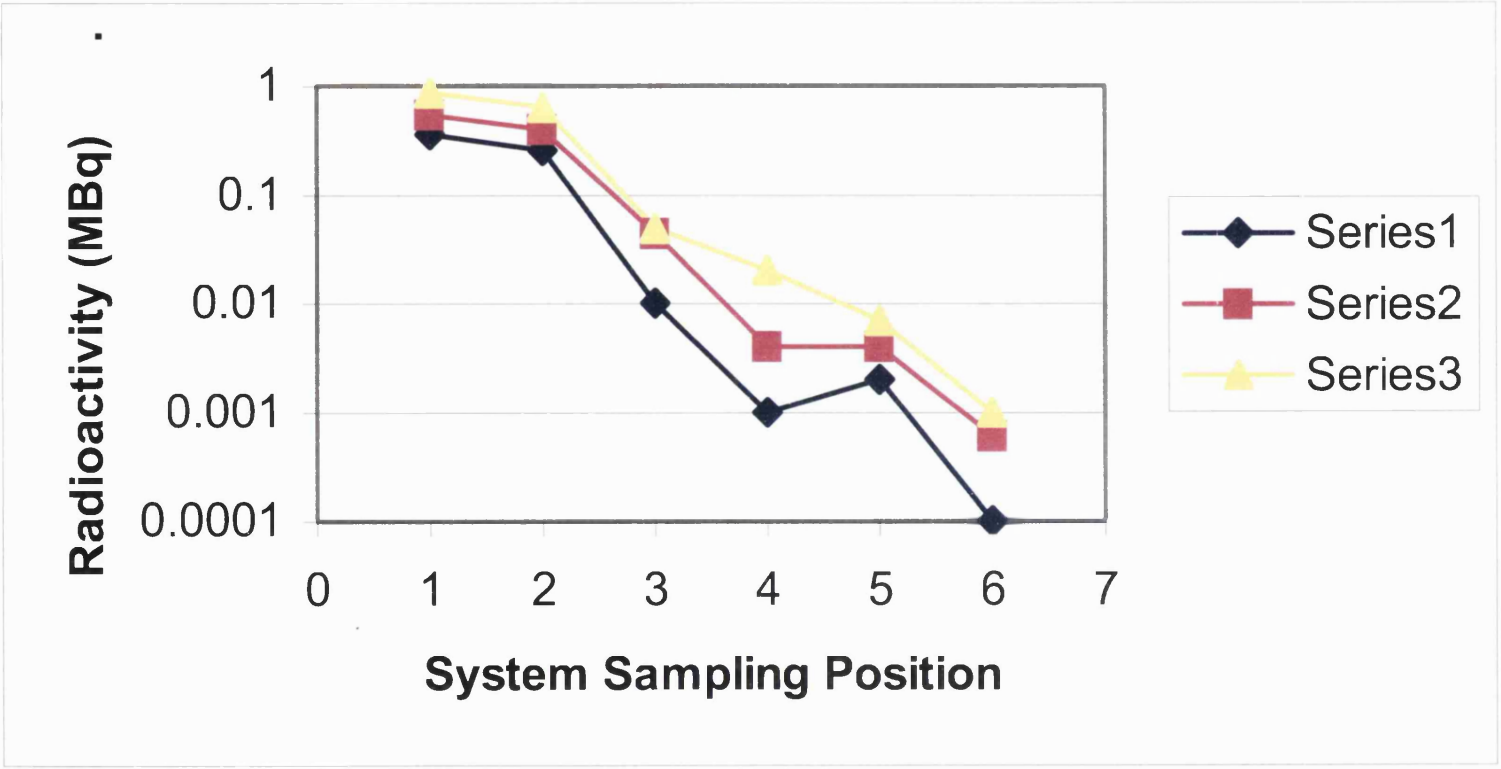


Figure 4.3j shows the relative differences in activity on specimens before and after the decontamination treatment, and Figure 4.3k describes the spread of contamination through the system. Here sampling positions (1 to 6) correspond to activity removed (1), activity in hopper medium (2), activity in gravity settler medium (3), activity held on the system walls to the gravity settler (4), activity in the cyclone fines (5), and finally activity held on the system walls down to the cyclone (6). Clearly contamination could spread and or migrate down through the system to the filters, so the life expectancy and waste volume of this equipment needs to be taken into account when considering the feasibility of employing this technology at the WAHF.

4.3.4 System Discharge Characterisation

In order to gain further data on the contamination transfer aspects of the process, two SEM 'sticky-stubs' were fitted to the upstream side of the HEPA filter, prior to installation of the filter. It was anticipated that the stubs would sample some of the particulate in the pre-filter airflow, giving an indication of the transfer of radioactive contamination from the waste items through the settler and cyclone to the filters. This would indicate what sort of challenge the filters might be expected to meet and the level of filter waste arisings that could be expected from this system. The 'sticky-stubs' were retrieved for SEM examination [95]. The stubs were gold sputter coated to prevent charging, and examined in a Cambridge S200 SEM, which had a Noran TN5500 EDX analyser attached. The use of a Field Emission SEM with EDX or Energy Dispersive X-Ray capabilities allow the irradiation by focused electron beam imaging secondary or backscattered electrons and energy analysis of X-Rays, thus the qualitative and quantitative analysis of small areas or components within the image area. The analyser is capable of detecting elements with an atomic number of 11 or larger. Secondary electron

(SE) images showing topographical contrast and back-scattered electron (BSE) images, which show mean atomic number contrast, were recorded using micrographs. The BSE images show higher atomic number areas as brighter regions.

Figure 4.3l shows the range of particles found in these samples. The higher magnification view in the second micrograph shows a range of particle shapes and sizes, including spheres, fibres and irregular shaped particles. Bulk EDX analysis of the spheres found them to contain Si, Ti, and some P (Figure 4.3m). These spheres appear to be agglomerates in which the more bright regions contain more Ti than the dark regions, which are more Si rich. The source of these particles is uncertain but the presence of Ti, which is used in its oxide form as a paint pigment, but flakes might be expected rather than spheres. Another possible source is the Rutile coating on welding rods, where spherical particles could be formed during the welding process.

The large bright particles in Figure 4.3l were found to contain Mg and Si and may also originate from deoxidisers commonly used in welding rod coatings. Figure 4.3n shows the EDX analysis of these particles. The other typical particles found consisted of mostly Fe. Figure 4.3o shows the SE image of one of these particles and Figure 4.3p shows the EDX analysis. The particles exhibit large amounts of plastic deformation. This may be swarf from the machining operations to fit pressure transducers. The fibres seen in Figure 4.3l were Si rich and may have originated from the HEPA filter to which they were attached, other wise they may be completely extraneous, being introduced when loading or unloading the filter and stubs from the system.

FIGURE 4.3l: PRE-FILTER AIRFLOW PARTICULATE STUDIES

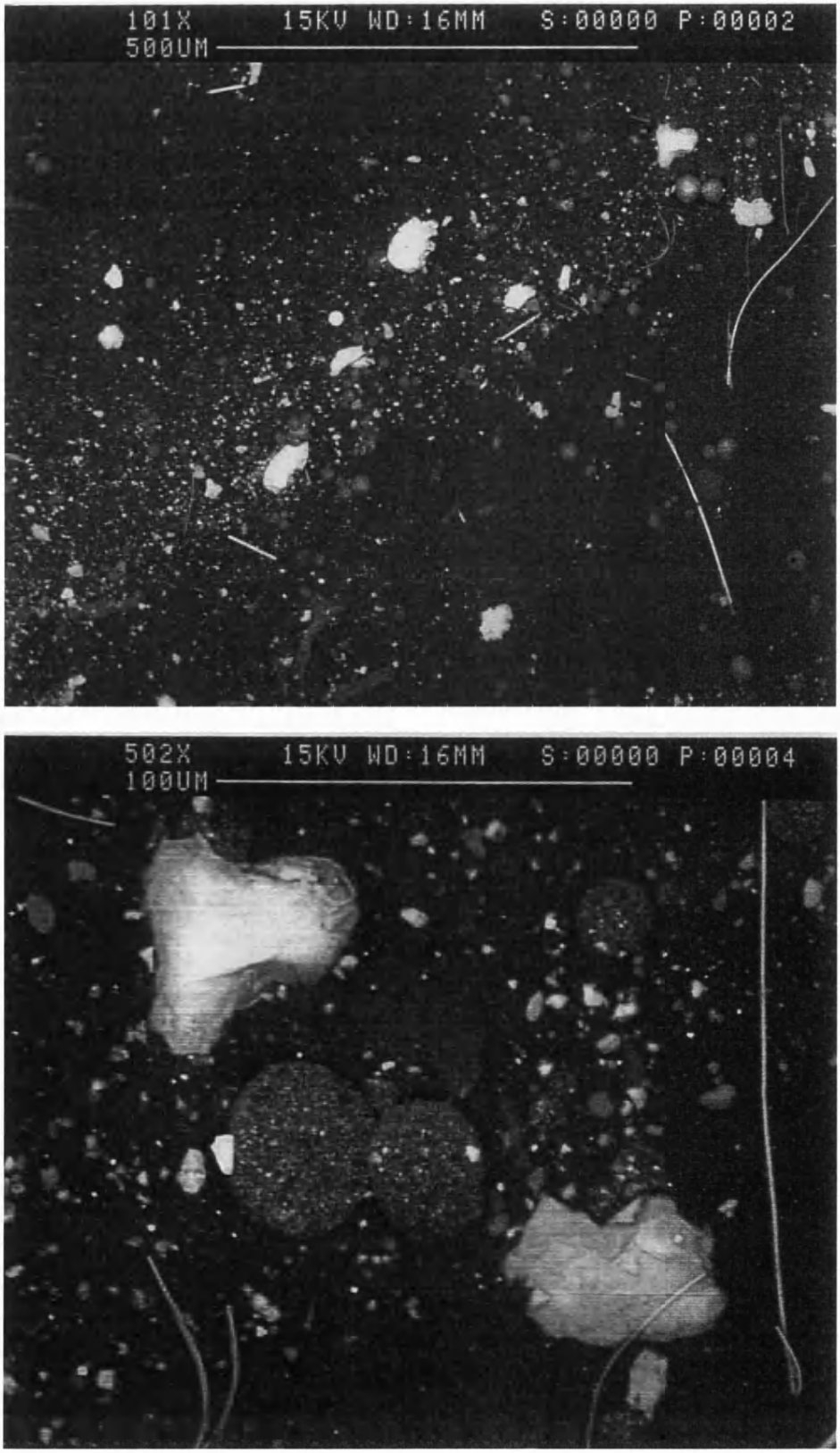


FIGURE 4.3m: EDX SPECTRUM OF SPHERES

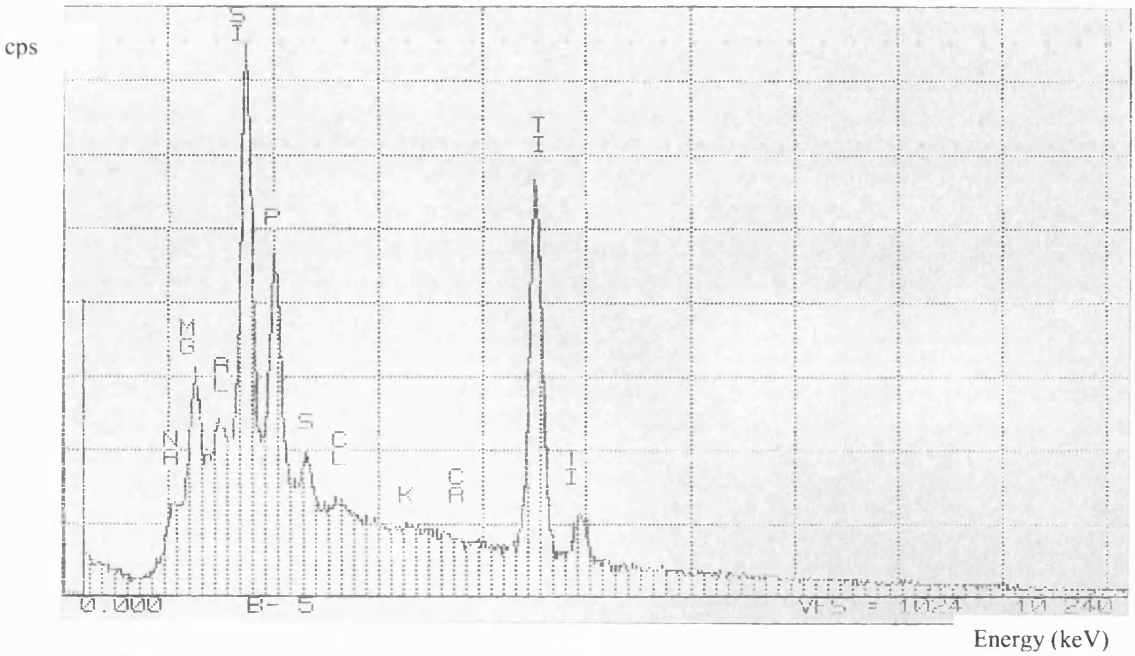


FIGURE 4.3n: EDX SPECTRUM OF BRIGHT PARTICLES

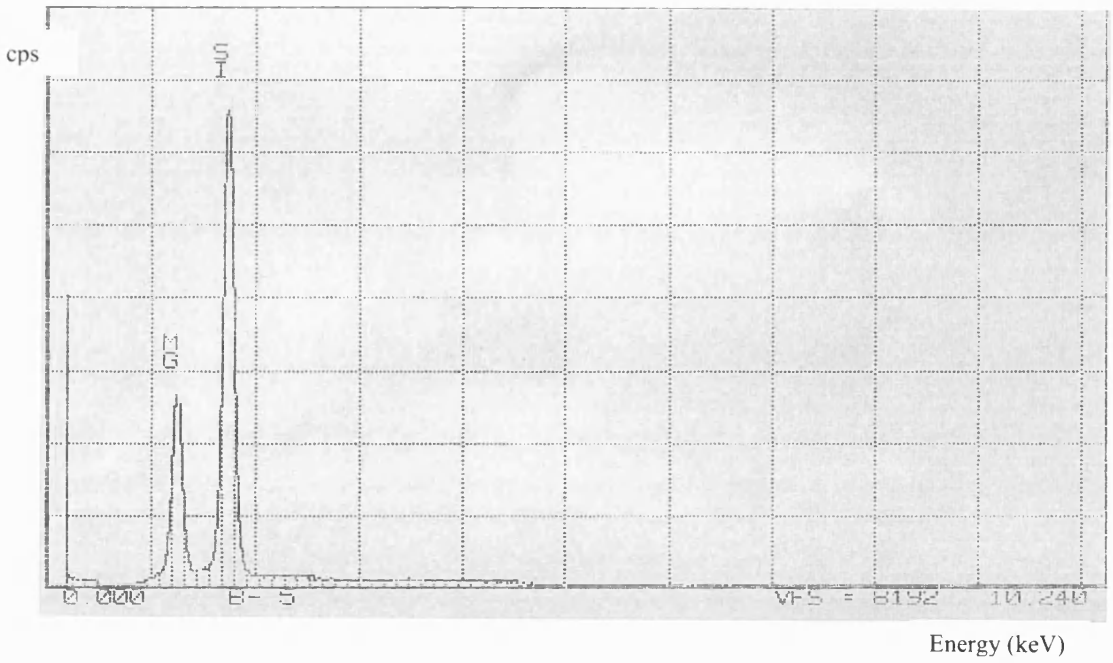


Figure 4.3q shows the largest of a few small U particles found, and the EDX spectrum in Figure 4.3r confirms this with peaks at the three main isotopes, which are not associated with any other elements. The appearance of the particle suggests that this is a fuel fragment. The particle exhibits what seem to be pores at its surface, which could be fission gas related. The angular nature of the particle suggests it may be the ceramic UO_2 fuel rather than the uranium metal form of fuel. The die inserts were used to declad uranium metal fuel, but it can not be ruled out that there were no UO_2 particles picked up by the specimens. The few particles found ranged in size from 2 to 20 μm across.

This led to some of the active sponge medium from the higher activity trial being examined. Figure 4.3s shows views of a piece of sponge medium and some of the particles found. A large amount of alumina debris from the medium was observed, and a number of Fe rich particles. The alumina particles were typically less than 100 μm in size, while the Fe rich particles ranged from 2 to 150 μm across. No U or other actinide particles were found, which leaves the source of the uranium particles unclear. The particle is ~20 μm across, and given the density of uranium it would appear unlikely that the particle defeated the abatement system. It is more likely that the particle has come from cross contamination from previous decontamination exercises on for example the milling machine or from the previous use to which the mobile fan-filter was put. No detectable radioactivity could be monitored on the filter suggesting that this was an isolated particle.

FIGURE 4.3o: SE IMAGE OF A LARGE FE RICH PARTICLE

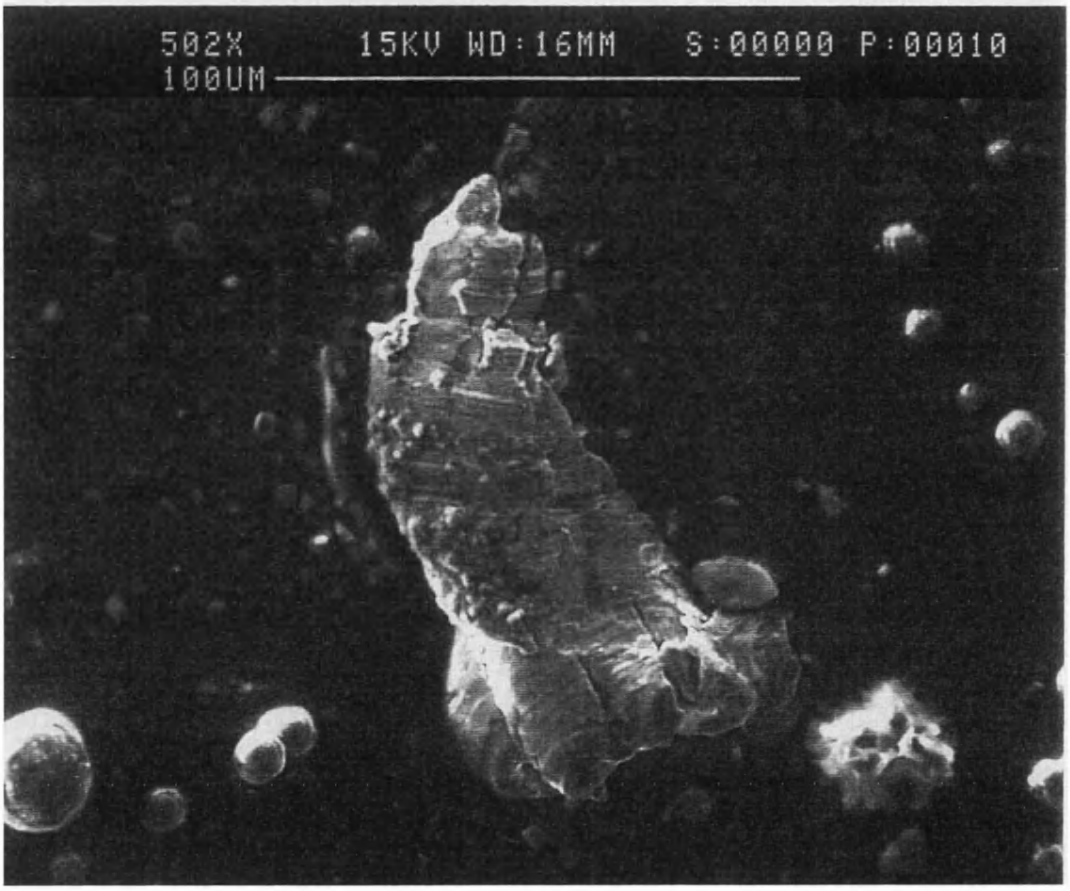


FIGURE 4.3p: EDX SPECTRUM OF THE LARGE PARTICLE IN FIGURE 4.3o

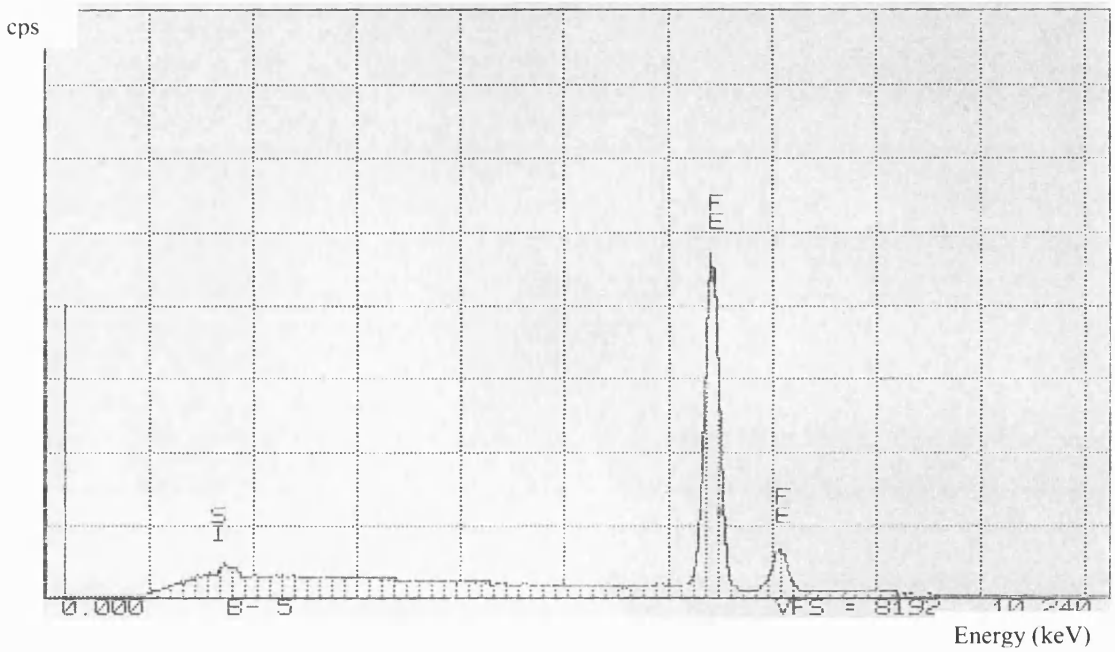


FIGURE 4.3q: SE IMAGE OF A SINGLE URANIUM PARTICLE

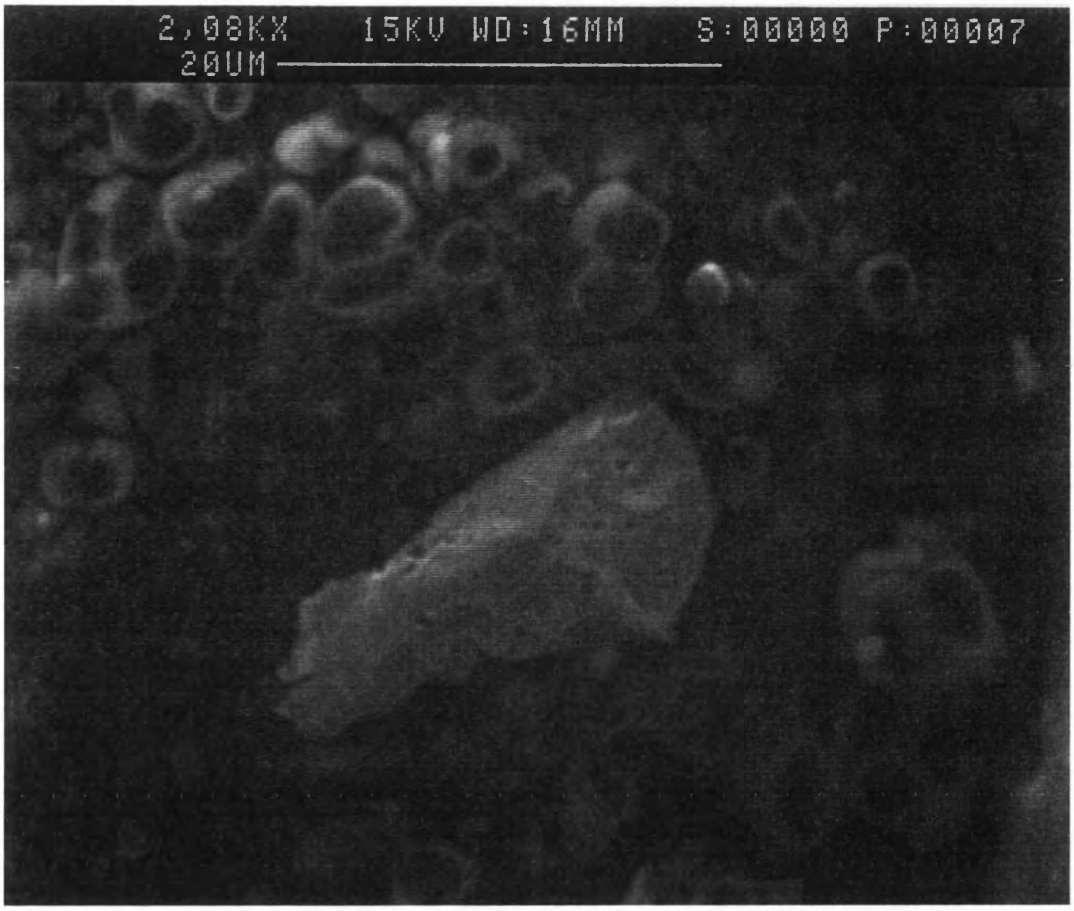


FIGURE 4.3r: EDX SPECTRUM OF THE URANIUM PARTICLE (FIG. 4.3q)

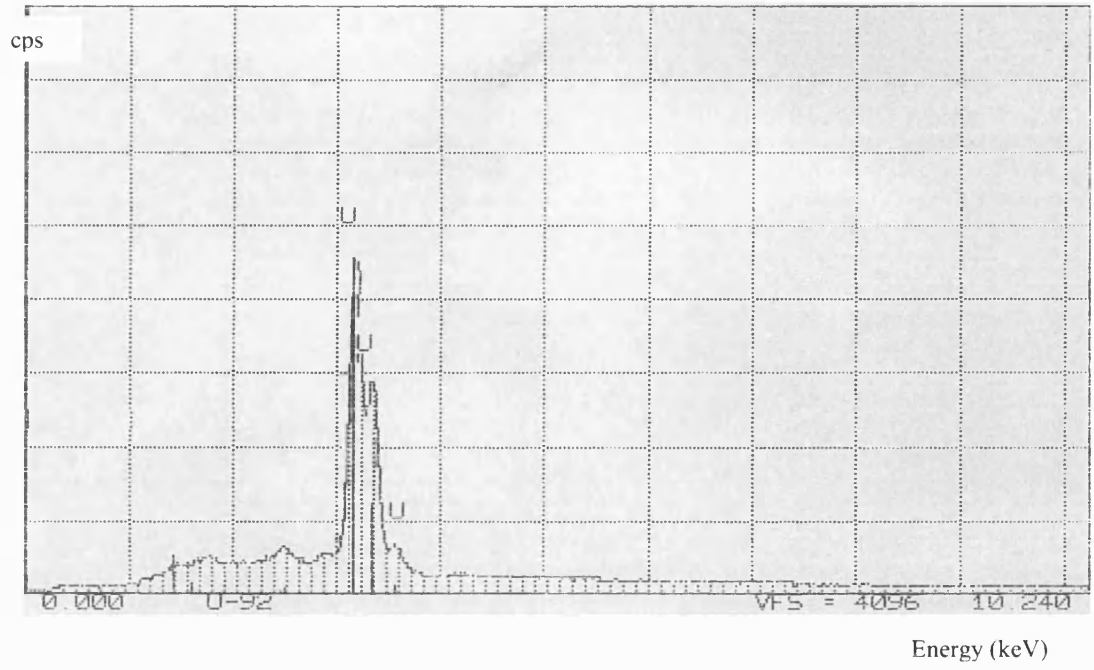


FIGURE 4.3s: BSE IMAGE OF USED SPONGE MEDIA FROM THE HIGHER ACTIVITY TRIAL

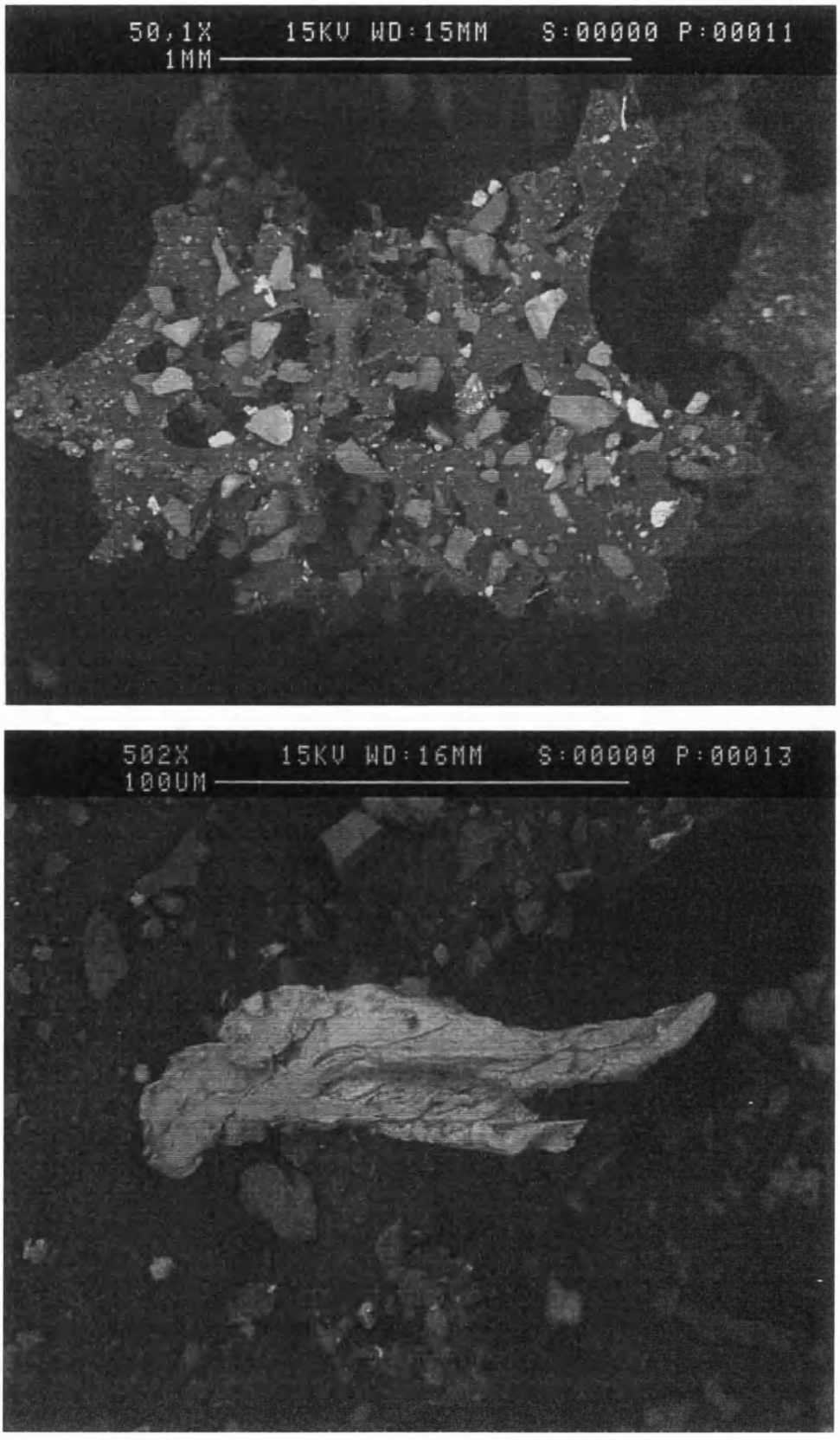
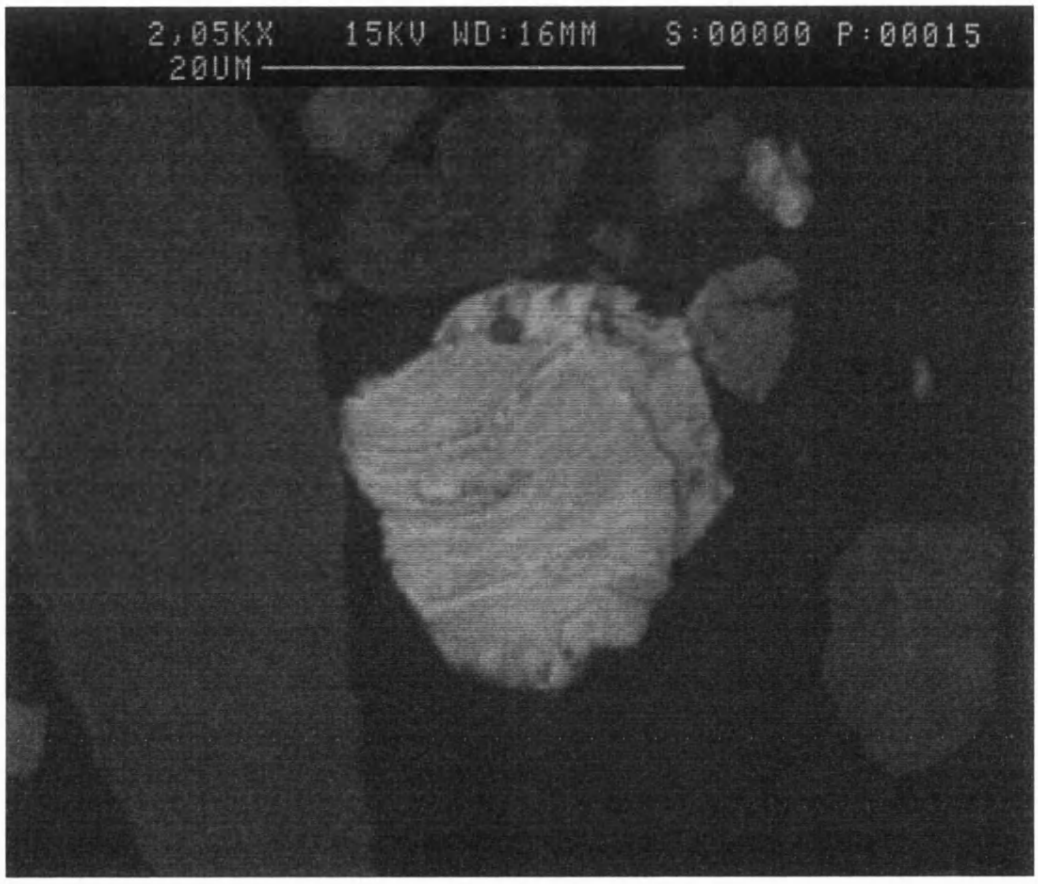


Figure 4.3s. Continued



4.3.5 Media Volume Reduction

The conceptual design described in Figure 3.3k, was built for trials with inactive media. Figure 4.3t shows the rig set up on a laboratory bench. The plunger with a block of fused medium is attached next to the rig. This is shown in more detail in Figure 4.3u.

The tube was set up with three heating plates capable of achieving a surface temperature of 200°C. Since the medium starts to break down at around this temperature [84] [8] a thermocouple was installed at a mid-point between the heating plates. This would ensure that the full circumference reaches a temperature above 130°C. Separate measurements of the heater and the thermocouple suggested that the heater plates would be at 150 to 160°C, but this measurement was taken without a medium charge present.

The tube was loaded with 332 mm of spent medium (received 5 recycles), and then successive loads were applied to the press plunger, and measurements of the reducing height of the medium were made. These measurements are presented as follows.

Applied Load(kg)	Media Ht(cm)	Volume(cc)	Comp.Ratio
0	33.2	3755	
3.8	18.5	2093	1.8
5.7	13.7	1550	2.4
15.5	11.7	1323	2.8

By simply adding a weight of 15.5 kg it was possible to achieve a volume reduction of nearly 3. The temperature reached 130°C at the mid-point between heaters after 23 minutes. It was held at this temperature for approximately 10 minutes, then the heaters were switched off, and the rig left to cool for about one hour. The medium block was left to cool sufficiently to ensure its surfaces did not tear on unloading.

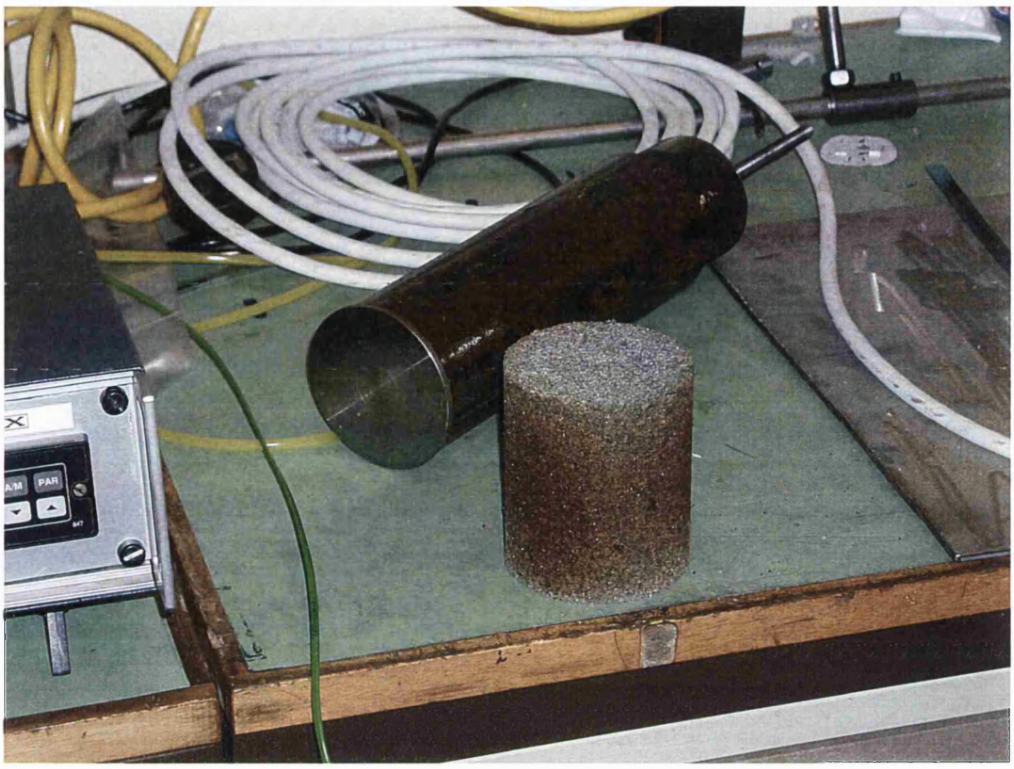
FIGURE 4.3t: POLYURETHANE SPONGE VOLUME REDUCTION TRIAL RIG

Rig to right with two of the three white heaters visible, plunger (central) with sponge Attached, and control and measurement equipment on the left.

FIGURE 4.3u: VOLUME REDUCED SPONGE MEDIA ATTACHED TO PRESS

Compressed and fused sponge medium attached to plunger

FIGURE 4.3v: BLOCK OF FUSED MEDIA REMOVED FROM PRESS



Fused sponge removed from plunger.

The plunger easily pushed the medium block out of the cylinder and stayed attached to the plunger end face. There was some concern as to whether the block would break up when

separation from this face was attempted, in case the lack of heating on this face had not fused the medium sufficiently. This proved to be unfounded and the medium block came away cleanly, and little or no medium fines broke off.

4.4 SUMMARY

The experimental results have been presented for initial non-radioactive work, VLLW, LLW and higher radioactivity trials. This has involved decontamination evaluation of the Sponge-jet process and volume reduction trials on the spent polyurethane foam medium. Studies have been conducted on the materials involved at every stage. This has gained an insight into the characteristics of the materials and their behaviour under decontamination conditions, irradiation, and volume reduction. Data has been collated on the decontamination performance of this technology as well as the volume reduction efficiency in order to make certain judgements about the feasibility of using Sponge-jet within an integrated waste management system for the WAHF.

CHAPTER 5. GENERAL DISUSSION

5.0 INTRODUCTION

When this work was proposed in 1996 Sponge-jet had only been used as a means of reducing radiation dose to workers during essential maintenance in a few limited applications. Its use as a decontamination tool for waste minimisation had not been explored. Today sponge blasting has been used in a much wider range of applications both for dose reduction and more relevantly for waste cleaning. This chapter will discuss the results of this research project and how it might be taken forward to be applied practically, as well as considering similar work undertaken elsewhere in recent years.

5.1 PRESENT STATUS OF NUCLEAR SPONGE-JET DEVELOPMENT

The Sponge-jet process has been studied extensively to assess its potential as a nuclear waste decontamination technique for use at the Windscale Active Handling Facilities (WAHF). The initial trials demonstrated the flexibility of the process, and that it could be aggressive enough to remove in ground radioactivity and or tenacious corrosion or painted layers that may harbour such contamination. The recycle-ability of the medium means the surface area of waste that can be treated for a given process and disposal cost justifies the decontamination of a large proportion of solid nuclear waste. This is clearly achievable for large mass/volume items such as flasks or large steel construction materials such as girders, but some high surface area/low volume wastes may need to be assessed more closely to be certain of the benefit of using this technology. The LLW trials were particularly successful in demonstrating the scope and capability of the Sponge-jet process as a decontamination tool. This ranged from simply stripping paint from metal surface to enable unequivocal radiation monitoring, to the removal of more highly radioactive surfaces from either waste metal or reusable tooling and equipment,

Sponge-jet can prove to be a useful LLW waste management tool. The higher activity trial results provide evidence that a flexible decontamination system can be developed for the WAHF that might reduce the waste generated across the whole spectrum of nuclear operations, including an in-cave facility for ILW.

Elsewhere Sponge-jet has been used on a number of occasions to remove paint or degrease surfaces down to clean metal such that the materials can be recycled [96, 97]. In some cases specialised medium was used to remove paint from critical surfaces for repainting and reuse [97]. This is particularly valuable for large amounts of painted metalwork in the nuclear industry, which will need such coatings removed before a robust radiological monitoring assessment can establish release for recycling/reuse. Active Sponge-jet work has also been carried out supporting decommissioning operations at Los Alamos National Laboratory (LANL) in the USA, and has seen waste scrap metal decontaminated using Sponge-jet [98] at a rate of some 200 m^3 $year^{-1}$, resulting in a saving of ~$173k $year^{-1}$. Assuming $1.5 to the pound sterling this equates to ~£865 m^{-3}. It is expected that these decommissioning operations will eventually generate 4000 m^3 of scrap metal waste, and if successfully decontaminated major cost savings will ensue. The LANL figures compare favourably with the predicted cost benefits from the LLW trials conducted at Windscale, where the mean savings for the girder (~£364 m^{-3}), and PRDO station (~£1800 m^{-3}) waste streams are just over £1000 m^{-3}. The approach adopted by the LANL appears to be very similar to the rig used in the LLW trials during this project. Currently (February 2004) Sponge-jet are estimating operational costs at ~£31 m^{-2}, which includes process set-up and set-down, man hours, waste disposal, and personal protective equipment. Capital costs for an integrated system, including recovery, recycling and reloading equipment is estimated at ~£45625. This cost does not include adaption for

nuclear operations where standards of containment and remote operability will need to be applied. This could easily double the cost of a stand alone integrated system for nuclear waste decontamination. Equipment hire is available but this is irrelevant for contamination reasons in the nuclear industry. Nevertheless when this is compared to the cost of disposal for LLW and ILW in particular these costs will easily be recouped following the treatment of relatively small volumes of waste.

One obstacle to realising this potential recycling route for metalwork arising from the nuclear industry is public/stakeholder perception. In the UK the British steel industry is reluctant to reuse steel that has been involved with radioactivity due to the perceptions of their customers, indeed the customers of Corus plc seek assurances that they will not use raw materials that contain radioactivity at all [99]. There is therefore little incentive to decontaminate LLW to free release levels if it is only going to be disposed to landfill as normal waste. It is unlikely that these attitudes will change in the near future. Nevertheless with increasing pressure on waste disposal facilities and increasing rates of decommissioning there is still going to be pressure to minimise waste where possible. One option might be to clean metal waste where viable and store it for specific reuse within the industry, for example, to manufacture structural materials to build new nuclear site facilities, or waste disposal containers. This would require dedicated facilities to process such waste; the current over capacity within the steel industry could allow for a niche market to be developed.

With respect to the operations at the WAHF there is also an immediate benefit in terms of reducing personal dose uptake during maintenance operations which will also minimise waste arising from contaminated tooling and equipment through reuse. Higher activity

trials have been undertaken and appear to demonstrate the further potential of the Sponge-jet technology to decontaminate potential ILW arising from the WAHF and the nuclear industry in general, within the safe shielded confines of the cave system. For some wastes it may even be viable to move the waste down the waste hierarchy from ILW (in-cave decontamination) to LLW, then from LLW (enclosure decontamination) to free release and recycling. If an in-cave system is successfully pursued, and suitable material handling, process automation and radiation/contamination monitoring is successfully engineered into the design a highly sophisticated and flexible waste processing facility could be developed. The results of this research suggest that such a facility is technically viable.

The ability to volume reduce the waste sponge medium has clear benefits in that it effectively brings a wider range of nuclear waste within the viability of the Sponge-jet process. Volume reduction studies to maximise the potential of using Sponge-jet at the WAHF have been ongoing in parallel with the blasting trials. Trials have led to studies into the medium itself which confirm that it is not a halogenated plastic and is free from chlorides; indeed studies of the cleaned surfaces suggest that any residues will not adversely effect the ongoing use of that surface or associated equipment. This suggests that the substitution of larger amounts of solid 'inert' waste with smaller volumes of compressed sponge medium will not compromise containment integrity during interim storage or final disposal. However, as with all plastics, polyurethane will breakdown under radiation, so the degradation mechanism and subsequent degradation products need to be further assessed to ensure there are no other adverse consequences e.g. nature of evolved gases. Confidence in the capability of the process will grow as more trials are

undertaken and information is added to this embryonic knowledge base for waste cleaning with this technology.

Table 5a summarises the experience gained at the WAHF. Based on these successes AEA Technology plc commissioned consultants [100] to design a more permanent system for routine operations in decontaminating LLW, that will integrate with the building ventilation, see Figure 5.1a. The key element here is the impact of the system's discharge on the buildings main header duct that ventilates the whole cave system within the WAHF. It has been assumed the maximum operating discharge of 0.2 $m^3 s^{-1}$ (12 $m^3 min^{-1}$). Based on the existing measured flow rates, volumetric discharges within the header duct will increase by ~5%. The effect of this increase in the volume flow rate on pressure within the header duct can be represented as follows.

$$P2 = P1 \times (Q2/Q1)^2$$

Where: P1 = Existing pressure within header
P2 = Increase in pressure within header
Q1 = Existing volume flow rate
Q2 = Increased volume flow rate

This showed that for a 5% increase in volume flow rate the pressure increases by nearly 10%. This could be accommodated by throttling back on the cave extract fans, or it might be considered to fall within acceptable operating tolerances for the building given adequate operating safeguards are built in to the Sponge-jet system e.g. interlocks and cut outs.

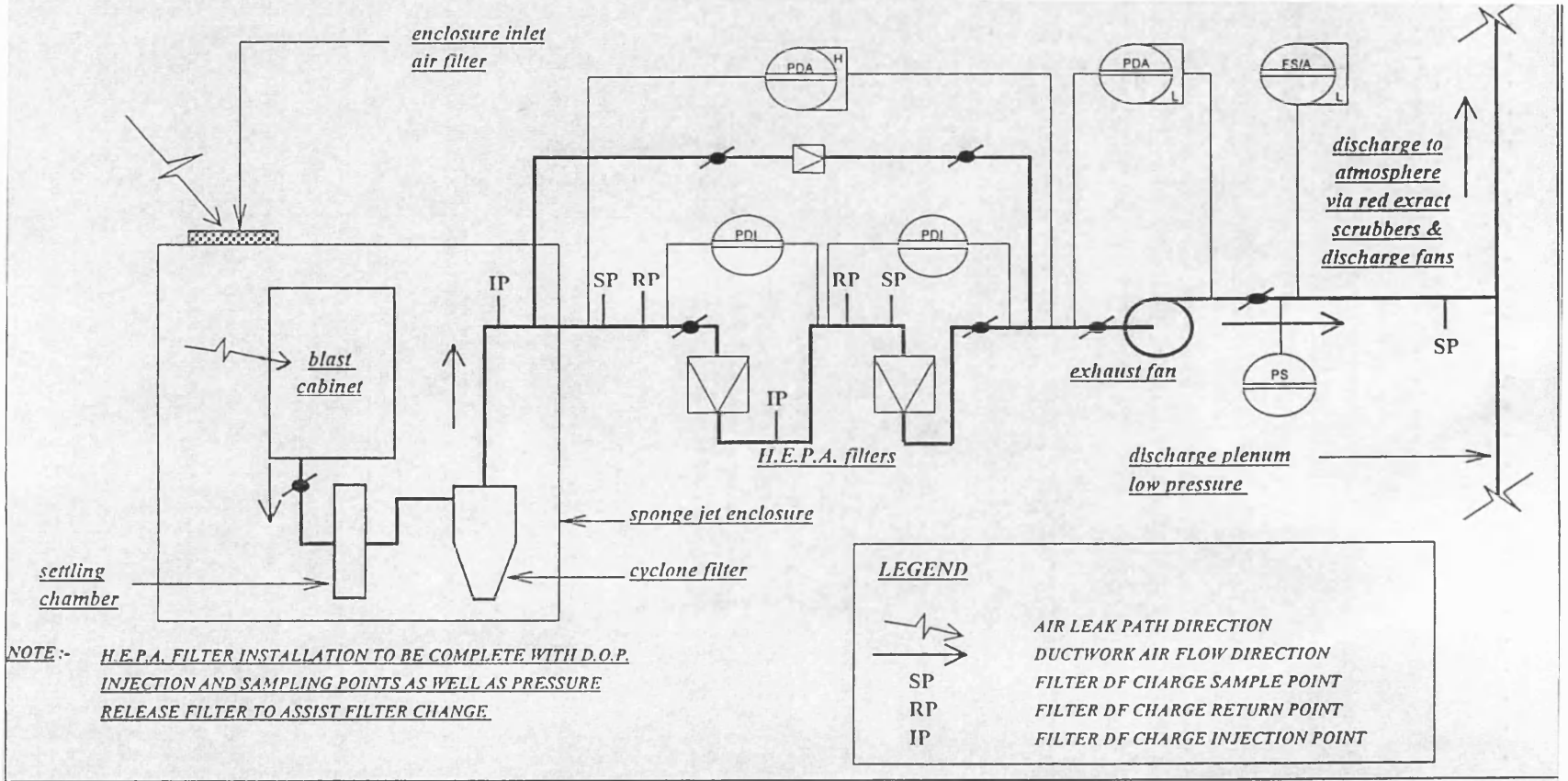
In recent year the UK Government has been preparing the way for major changes in the nuclear industry with the Energy Bill having been introduced to Parliament in November 2003, and the Energy Act has received its Royal assent in July 2004.

This legislation paves the way for a new approach to dealing with the UK nuclear liabilities. The Government is well on the way to setting up the Nuclear Decommissioning Authority (NDA) which will come in to force at the beginning of April 2005. The NDA will own all the nuclear liabilities and aims to reduce the risks posed by these old plants by speeding up the process of decommissioning. This is going to cost a lot of money and as always value for money and the best use of limited resources will be high on the agenda. This may involve the use of novel approaches to waste management, of which Sponge-jet may be one such approach.

In 2001 the IAEA published a technical document advising on the approaches to be adopted by nuclear industry when decommissioning nuclear facilities [101]. This covered the selection of decontamination and decommissioning techniques in order to minimise the generation of radioactive waste. Amongst many other considerations this report advises that when selecting a specific technique for decontamination the requirements of safety, efficiency, cost effectiveness, waste minimisation and the feasibility of industrialisation must be taken into account. The work undertaken as part of this research project has gone a very long way to address these requirements. The process of designing the test rigs in order to conduct the trials and the results of monitoring data from the actual trials supports the case for a full-scale facility. The integration of such technology into a shielded facility like the WAHF means that radiation hazards to workers and the environment are reduced. The operating envelope of the Sponge-jet technology as applied to a nuclear decontamination arena has been defined to a substantial degree for the WAHF, and it can result in reduced dose uptake to operators from waste disposal operations. In conducting these studies a close interest in the cost-benefit has been maintained. Waste must be assessed and characterised appropriately to ensure this

technology will be the BPEO for treating that waste on a case by case basis. Not all waste will be suitable for dry decontamination treatment. The development of prototype systems and test rigs has demonstrated that the technology is amenable to automation and remote operation, therefore reducing labour, and hands-on work, which in turn leads to reduced dose uptake.

FIGURE 5.1a. OUTLINE DESIGN PLAN FOR A PERMANENTLY INSTALLED LLW DECONTAMINATION SYSTEM



NOTE :- H.E.P.A. FILTER INSTALLATION TO BE COMPLETE WITH D.O.P. INJECTION AND SAMPLING POINTS AS WELL AS PRESSURE RELEASE FILTER TO ASSIST FILTER CHANGE.

Title:
VENTILATION FLOW DIAGRAM - OUTLINE BID PROPOSAL FOR CABINET VENILATION CONTAMINATION

Rev:	Drawn by:	Approved by:
A	T QUINN	

TABLE 5.1a. A SUMMARY OF WASTE TREATMENT AT THE WINDSCALE ACTIVE HANDLING FACILITIES

AEA TECHNOLOGY SPONGE BLASTING
KNOWLEDGE BASE

PROCESS EXPERIENCE
SUMMARY

PROCESS DESCRIPTION	Material	Surface	Contam. Form	Activity (Bq)	Radiation (mSv)	Surface Area (m2)	Spec. Activity (Bq/m2)	Media Type	Vol. Used (m3)	Media use	Blast Pressure (psi)	Est. Df	Surface Roughness (Ra)	Comments
Trial on SG tube	inconel	Ox.Scale	fixed	3.2M				Brown		3 Passes	30	2.3	4	Trials on small lengths of tubing[100]
Trial on SG tube	inconel	Ox.Scale	fixed	3.4M				Brown		Once-through	30	3.7	3.8	"
Trial on SG tube	inconel	Ox.Scale	fixed	3.6M				Red		3 Passes	30	8.4	15.8	"
Trial on SG tube	inconel	Ox.Scale	fixed	3.7M				Red		Once-through	30	2.1	15.9	"
Pipe End Decontam.- Best	St-Steel	Cor.Scale	Fixed		up to 150*	1.3		Silver	0.3	Once-through	70	up to 7.5	20-30	Data from J Flaherty, AEAT @Nivelles[101]
- Maguire 1	St-Steel	Cor.Scale	Fixed		20	1.3?		Silver?	0.3?	Once-through	?	3.3	20-30?	Data from RM Beinstein[52]
- Carawba	St-Steel	Cor.Scale	Fixed		31	1.3?		Silver?	0.3?	Once-through	?	3.8	20-30?	"
- N. Anna	St-Steel	Cor.Scale	Fixed		54	1.3?		Silver?	0.3?	Once-through	?	3.8	20-30?	"
- V. C. Summer	St-Steel	Cor.Scale	Fixed		60	1.3?		Silver?	0.3?	Once-through	?	4.9	20-30?	"
- C N de Almarez	St-Steel	Cor.Scale	Fixed		25	1.3?		Silver?	0.3?	Once-through	?	2.8	20-30?	"
PRDO Decon trial	Cast Steel	Rust & Paint	Loose&fixed	0.7M		1.5		Silver	0.7	Once-through	70	3.5		Controlled area trial
- overall	Cast Steel	Rust & Paint	Loose&fixed	19.6M		42		Silver	0.7	Recycled	70	>100		Three PRDO's cleaned to free release
Cave 11 Milling Machine	Steel	Grease	Loose		18	2		Green	0.06	Once-through	70	7.2		HPS/Fitter Dose Uptake
Die inserts Overall	Steel	In ground U	Fixed + Loose	7M	3	0.075		Silver	0.019	Recycled	70	1.5 (17max)		Incomplete decontam. Media not spent

5.2 MODELLING SPONGE-JET PERFORMANCE

The continuation of higher active trials will enable the collection of additional data to assist system development for deployment in to a cave situation. The design consideration will need to take account of remote replacement of parts, which in time may succumb to erosion, and protective monitoring to ensure contamination migration does not challenge filters. The evidence following these trials using basic mild steel suggests that a suitably durable system can be designed. The data obtained from these early trials and future work can be used to provide predictive spreadsheets that enable the waste management task to be considered in terms of source term and the decontamination level to be expected for each recycle. This should enable predictions of the volume of new medium required for decontaminating the solid waste, the resulting volumes of secondary waste medium. Eventually other factors such as plant and filter life cycle will be available to provide further confidence that all plant life cycle factors are accounted for in decisions on whether the Sponge-jet process is used for nuclear waste treatment problems.

Table 5.2a, spreadsheets 1-4 show predictive spreadsheets for various idealised scenarios where specific radioactivity levels on waste and the radioactivity reduction of the waste, that may be expected following each blasting recycle. The decontamination levels in these examples are based on the experience gained during the trials and have assumed specific surface area to mass ratio, within a fixed waste volume occupancy. Specific levels of radioactive contamination are then considered against each pass using recycled sponge, based on Dfs achieved in the trials. This should provide an operational tool allowing an operator to consider the level or degree of sponge blasting required for a particular waste treatment problem, and whether to apply technology to their specific

problem. The spreadsheet can be altered by inputting specific data for the problem under consideration, either in terms of surface area, or mass involved, but also different decontamination factors can be input as more information is gained about the process.

Table 5.2a uses the information gained during the higher activity decontamination trials, and spreadsheets 1-4 standardise on a 1 m^2 surface area related to a mass of steel occupying a ~0.07m^3 volume. Since waste occupying such a volume may range from a solid mass down to thin shell, these spreadsheets consider scenario that relate to a solid weighing ~538 kg, a steel waste item where 50% of the volume has accessible space/voids (weighing ~269 kg), an item with 75% accessible space (~134 kg), and finally a waste item occupying the same volume with 85% space (~80 kg). Clearly these parameters can be adjusted to suite the particular waste disposal problem facing the operator, but serve to describe how the Sponge-jet process might perform as a waste decontamination tool. Waste items exhibiting mean dose rates from 5 $\mu Sv\ hr^{-1}$ to 10 $Sv\ hr^{-1}$ are considered. Table 5.2a, spreadsheet 1 predicts the decontamination of a solid steel (a 1 m^2 total surface area and ~538 kg) waste item. This would be consigned for disposal as LLW up to ~80 $mSv\ hr^{-1}$, which through the conversions used here equates a total activity content of 6.4 GBq and a specific activity of 12 $kBq\ g^{-1}$.

As mentioned earlier, not all waste items will have the same surface area or mass, so the spreadsheets in Table 5.2a, spreadsheets 2-4 compare waste items with a similar surface area, but progressively more void/spaces, within the same overall disposal volume. Where a waste item mass falls relative to the surface area, waste will be categorised as ILW at lower radiation levels. These spreadsheets show that the waste will be consigned at progressively lower radiation levels (down to nearly 10 $mSv\ hr^{-1}$ at ~80 kg and 85%

space) due to the lower weight of the waste items. These spreadsheets show that it is feasible to decontaminate wastes from ILW to LLW within certain number of blast cycles. There are uncertainties about the ability of the Sponge-jet process to decontaminate LLW from just below the ILW threshold, down to free release levels within the five recycles considered in these spreadsheets. This area would need further studies with more medium to ascertain whether decontamination to free release would be viable. LLW up to ~10mSv hr^{-1} within these scenario could be cleaned to free release levels.

Table 5.2b examines the sponge waste volumes that would ensue from these scenarios, the potential radioactivity content and consequent disposal routes. LLW waste up to radiation dose rates of 2 mSv hr^{-1} will give rise to waste sponge that is itself LLW, so the benefits can be observed through direct comparison of waste volumes. For passes 1, 2, 3, 4 and 5, ~0.0015 m^3, ~0.0029 m^3, 0.0044 m^3, 0.0058 m^3 and 0.0073 m^3 of sponge waste would accrue, respectively. This can be compared directly to the volume of the waste that was decontaminated, 0.07 m^3. This represents between a 10 and 50 fold saving, from between ~£4.50 and ~£22 for the disposal of the sponge and ~£210 for the steel waste. Above the 2 mSv hr^{-1} level up to ~10 mSv hr^{-1} Table 5c confirms the uncertainties mentioned earlier, in that there is a possibility that LLW waste could be decontaminated, but remain LLW following treatment, and the spent sponge may have to be disposed of as ILW. Above radiation dose rates of ~10 mSv hr^{-1} the steel waste is expected to be disposed of as ILW, decontamination with Sponge-jet suggests the steel work would go as LLW while smaller volumes of ILW sponge would accrue. If the ILW costs are conservatively assumed to be £0.5 Million per metre cubed, then the sponge waste disposal cost would be between ~£750 and £3650, which compares favourably with the

disposal of 0.07 m^3 of steel work at ~£35000. This is a similar proportional benefit to that predicted for the LLW to free release benefits.

One concern in moving waste from one classification to another will be the impact it may have on limited disposal resources. Drigg in West Cumbria is the only viable long-term disposal route for LLW; diversion of ex-solid ILW volumes may exhaust the Drigg capacity faster. But this should not be a problem if concurrently an integrated waste management system decontaminated LLW down to free release levels. Since the largest nuclear waste volumes fall into the LLW categorisation, these volumes will more than out weigh the volumes added to the Drigg route from the ex-solid ILW waste. It is therefore highly unlikely that disposal management problems will arise if the process is integrated across the whole nuclear waste range. This relies on there being a satisfactory reuse mechanism/value for the free released steelwork, in effect an integrated waste strategy for the UK nuclear industry not just the WAHF. If these benefits can be realised for what are often highly expensive plant items in the nuclear industry then the savings to the industry and the UK taxpayer could be compounded.

TABLE 5.2a. PREDICTIVE TABLES FOR VARIOUS SPONGE-JET DECONTAMINATION SCENARIO

1. Based on the higher activity trial a solid 0.07 m^3 block of steel with a 1 m^2 surface area

Decontamination From Each Recycling Operation

Specify Df For each Pass;	PASS 1 =	17	based on a 1 sq.m surface area
	PASS 2 =	12	(Df's corrected upwards slightly to take account of a full media recycles)
	PASS 3 =	7	
	PASS 4 =	2	
	PASS 5 =	1.4	
Total Df =		38	
Mean Df =		8	
Monitor conversion factor =		8	Where 100microSieverts/hr is equivalent to 800Bq/sq.cm for conversion from RO2 to BP3 measurements
Total Sample Area =		10000	sq.cm Assumes a cube with six sides ~41cm sq. (0.40824829m)
Mass of waste (g) =		537600	Assumes 0.07cu.metre volume of steel waste at 7.8te/cu.metre = 0.54te (537.6kgs) of waste
Initial Trial Media Volume =		25696	cu.cm Link to waste volume sheet(This assumes the worst case coverage see Chapter 4.1-recycling)

Dose Rate	Start Activity	Specific Start	Pass 1	Specific P1	Pass 2	Specific P2	Pass 3	Specific P3	Pass 4	Specific P4	Pass 5	Specific P5
(microSv/hr)	(Bq)	Act'y(Bq/g)	Activity(Bq)	Act'y(Bq/g)	Activity(Bq)	Act'y(Bq/g)	Activity(Bq)	Act'y(Bq/g)	Activity(Bq)	Act'y(Bq/g)	Activity(Bq)	Act'y(Bq/g)
1.00E+07	8.00E+11	1.49E+06	4.71E+10	8.75E+04	3.92E+09	7.29E+03	5.60E+08	1.04E+03	2.80E+08	5.21E+02	2.00E+08	3.72E+02
9.00E+06	7.20E+11	1.34E+06	4.24E+10	7.88E+04	3.53E+09	6.57E+03	5.04E+08	9.38E+02	2.52E+08	4.69E+02	1.80E+08	3.35E+02
8.00E+06	6.40E+11	1.19E+06	3.76E+10	7.00E+04	3.14E+09	5.84E+03	4.48E+08	8.34E+02	2.24E+08	4.17E+02	1.60E+08	2.98E+02
7.00E+06	5.60E+11	1.04E+06	3.29E+10	6.13E+04	2.75E+09	5.11E+03	3.92E+08	7.29E+02	1.96E+08	3.65E+02	1.40E+08	2.61E+02
6.00E+06	4.80E+11	8.93E+05	2.82E+10	5.25E+04	2.35E+09	4.38E+03	3.36E+08	6.25E+02	1.68E+08	3.13E+02	1.20E+08	2.23E+02
5.00E+06	4.00E+11	7.44E+05	2.35E+10	4.38E+04	1.96E+09	3.65E+03	2.80E+08	5.21E+02	1.40E+08	2.61E+02	1.00E+08	1.86E+02
4.70E+06	3.76E+11	6.99E+05	2.21E+10	4.11E+04	1.84E+09	3.43E+03	2.63E+08	4.90E+02	1.32E+08	2.45E+02	9.40E+07	1.75E+02
4.40E+06	3.52E+11	6.55E+05	2.07E+10	3.85E+04	1.73E+09	3.21E+03	2.46E+08	4.59E+02	1.23E+08	2.29E+02	8.80E+07	1.64E+02
4.10E+06	3.28E+11	6.10E+05	1.93E+10	3.59E+04	1.61E+09	2.99E+03	2.30E+08	4.27E+02	1.15E+08	2.14E+02	8.20E+07	1.53E+02
3.80E+06	3.04E+11	5.65E+05	1.79E+10	3.33E+04	1.49E+09	2.77E+03	2.13E+08	3.96E+02	1.06E+08	1.98E+02	7.60E+07	1.41E+02
3.50E+06	2.80E+11	5.21E+05	1.65E+10	3.06E+04	1.37E+09	2.55E+03	1.96E+08	3.65E+02	9.80E+07	1.82E+02	7.00E+07	1.30E+02
3.20E+06	2.56E+11	4.76E+05	1.51E+10	2.80E+04	1.25E+09	2.33E+03	1.79E+08	3.33E+02	8.96E+07	1.67E+02	6.40E+07	1.19E+02
2.90E+06	2.32E+11	4.32E+05	1.36E+10	2.54E+04	1.14E+09	2.12E+03	1.62E+08	3.02E+02	8.12E+07	1.51E+02	5.80E+07	1.08E+02
2.60E+06	2.08E+11	3.87E+05	1.22E+10	2.28E+04	1.02E+09	1.90E+03	1.46E+08	2.71E+02	7.28E+07	1.35E+02	5.20E+07	9.68E+01
2.30E+06	1.84E+11	3.42E+05	1.08E+10	2.01E+04	9.02E+08	1.68E+03	1.29E+08	2.40E+02	6.44E+07	1.20E+02	4.60E+07	8.56E+01
2.00E+06	1.60E+11	2.98E+05	9.41E+09	1.75E+04	7.84E+08	1.46E+03	1.12E+08	2.08E+02	5.60E+07	1.04E+02	4.00E+07	7.44E+01
1.80E+06	1.44E+11	2.68E+05	8.47E+09	1.58E+04	7.06E+08	1.31E+03	1.01E+08	1.88E+02	5.04E+07	9.38E+01	3.60E+07	6.70E+01

1.60E+06	1.28E+11	2.38E+05	7.53E+09	1.40E+04	6.27E+08	1.17E+03	8.96E+07	1.67E+02	4.48E+07	8.34E+01	3.20E+07	5.95E+01
1.40E+06	1.12E+11	2.08E+05	6.59E+09	1.23E+04	5.49E+08	1.02E+03	7.84E+07	1.46E+02	3.92E+07	7.29E+01	2.80E+07	5.21E+01
1.20E+06	9.60E+10	1.79E+05	5.65E+09	1.05E+04	4.71E+08	8.75E+02	6.72E+07	1.25E+02	3.36E+07	6.25E+01	2.40E+07	4.47E+01
1.00E+06	8.00E+10	1.49E+05	4.71E+09	8.75E+03	3.92E+08	7.29E+02	5.60E+07	1.04E+02	2.80E+07	5.21E+01	2.00E+07	3.72E+01
9.00E+05	7.20E+10	1.34E+05	4.24E+09	7.88E+03	3.53E+08	6.57E+02	5.04E+07	9.38E+01	2.52E+07	4.69E+01	1.80E+07	3.35E+01
8.00E+05	6.40E+10	1.19E+05	3.76E+09	7.00E+03	3.14E+08	5.84E+02	4.48E+07	8.34E+01	2.24E+07	4.17E+01	1.60E+07	2.98E+01
7.00E+05	5.60E+10	1.04E+05	3.29E+09	6.13E+03	2.75E+08	5.11E+02	3.92E+07	7.29E+01	1.96E+07	3.65E+01	1.40E+07	2.61E+01
6.00E+05	4.80E+10	8.93E+04	2.82E+09	5.25E+03	2.35E+08	4.38E+02	3.36E+07	6.25E+01	1.68E+07	3.13E+01	1.20E+07	2.23E+01
5.00E+05	4.00E+10	7.44E+04	2.35E+09	4.38E+03	1.96E+08	3.65E+02	2.80E+07	5.21E+01	1.40E+07	2.61E+01	1.00E+07	1.86E+01
4.50E+05	3.60E+10	6.70E+04	2.12E+09	3.94E+03	1.76E+08	3.28E+02	2.52E+07	4.69E+01	1.26E+07	2.34E+01	9.00E+06	1.67E+01
4.00E+05	3.20E+10	5.95E+04	1.88E+09	3.50E+03	1.57E+08	2.92E+02	2.24E+07	4.17E+01	1.12E+07	2.08E+01	8.00E+06	1.49E+01
3.50E+05	2.80E+10	5.21E+04	1.65E+09	3.06E+03	1.37E+08	2.55E+02	1.96E+07	3.65E+01	9.80E+06	1.82E+01	7.00E+06	1.30E+01
3.00E+05	2.40E+10	4.46E+04	1.41E+09	2.63E+03	1.18E+08	2.19E+02	1.68E+07	3.13E+01	8.40E+06	1.56E+01	6.00E+06	1.12E+01
2.50E+05	2.00E+10	3.72E+04	1.18E+09	2.19E+03	9.80E+07	1.82E+02	1.40E+07	2.61E+01	7.00E+06	1.30E+01	5.00E+06	9.30E+00
2.00E+05	1.60E+10	2.98E+04	9.41E+08	1.75E+03	7.84E+07	1.46E+02	1.12E+07	2.08E+01	5.60E+06	1.04E+01	4.00E+06	7.44E+00
1.80E+05	1.44E+10	2.68E+04	8.47E+08	1.58E+03	7.06E+07	1.31E+02	1.01E+07	1.88E+01	5.04E+06	9.38E+00	3.60E+06	6.70E+00
1.60E+05	1.28E+10	2.38E+04	7.53E+08	1.40E+03	6.27E+07	1.17E+02	8.96E+06	1.67E+01	4.48E+06	8.34E+00	3.20E+06	5.95E+00
1.40E+05	1.12E+10	2.08E+04	6.59E+08	1.23E+03	5.49E+07	1.02E+02	7.84E+06	1.46E+01	3.92E+06	7.29E+00	2.80E+06	5.21E+00
1.20E+05	9.60E+09	1.79E+04	5.65E+08	1.05E+03	4.71E+07	8.75E+01	6.72E+06	1.25E+01	3.36E+06	6.25E+00	2.40E+06	4.47E+00
1.00E+05	8.00E+09	1.49E+04	4.71E+08	8.75E+02	3.92E+07	7.29E+01	5.60E+06	1.04E+01	2.80E+06	5.21E+00	2.00E+06	3.72E+00
9.00E+04	7.20E+09	1.34E+04	4.24E+08	7.88E+02	3.53E+07	6.57E+01	5.04E+06	9.38E+00	2.52E+06	4.69E+00	1.80E+06	3.35E+00
8.00E+04	6.40E+09	1.19E+04	3.76E+08	7.00E+02	3.14E+07	5.84E+01	4.48E+06	8.34E+00	2.24E+06	4.17E+00	1.60E+06	2.98E+00
7.00E+04	5.60E+09	1.04E+04	3.29E+08	6.13E+02	2.75E+07	5.11E+01	3.92E+06	7.29E+00	1.96E+06	3.65E+00	1.40E+06	2.61E+00
6.00E+04	4.80E+09	8.93E+03	2.82E+08	5.25E+02	2.35E+07	4.38E+01	3.36E+06	6.25E+00	1.68E+06	3.13E+00	1.20E+06	2.23E+00
5.00E+04	4.00E+09	7.44E+03	2.35E+08	4.38E+02	1.96E+07	3.65E+01	2.80E+06	5.21E+00	1.40E+06	2.61E+00	1.00E+06	1.86E+00
4.50E+04	3.60E+09	6.70E+03	2.12E+08	3.94E+02	1.76E+07	3.28E+01	2.52E+06	4.69E+00	1.26E+06	2.34E+00	9.00E+05	1.67E+00
4.00E+04	3.20E+09	5.95E+03	1.88E+08	3.50E+02	1.57E+07	2.92E+01	2.24E+06	4.17E+00	1.12E+06	2.08E+00	8.00E+05	1.49E+00
3.50E+04	2.80E+09	5.21E+03	1.65E+08	3.06E+02	1.37E+07	2.55E+01	1.96E+06	3.65E+00	9.80E+05	1.82E+00	7.00E+05	1.30E+00
3.00E+04	2.40E+09	4.46E+03	1.41E+08	2.63E+02	1.18E+07	2.19E+01	1.68E+06	3.13E+00	8.40E+05	1.56E+00	6.00E+05	1.12E+00
2.50E+04	2.00E+09	3.72E+03	1.18E+08	2.19E+02	9.80E+06	1.82E+01	1.40E+06	2.61E+00	7.00E+05	1.30E+00	5.00E+05	9.30E-01
2.00E+04	1.60E+09	2.98E+03	9.41E+07	1.75E+02	7.84E+06	1.46E+01	1.12E+06	2.08E+00	5.60E+05	1.04E+00	4.00E+05	7.44E-01
1.50E+04	1.20E+09	2.23E+03	7.06E+07	1.31E+02	5.88E+06	1.09E+01	8.40E+05	1.56E+00	4.20E+05	7.82E-01	3.00E+05	5.58E-01
1.00E+04	8.00E+08	1.49E+03	4.71E+07	8.75E+01	3.92E+06	7.29E+00	5.60E+05	1.04E+00	2.80E+05	5.21E-01	2.00E+05	3.72E-01
9.00E+03	7.20E+08	1.34E+03	4.24E+07	7.88E+01	3.53E+06	6.57E+00	5.04E+05	9.38E-01	2.52E+05	4.69E-01	1.80E+05	3.35E-01
8.00E+03	6.40E+08	1.19E+03	3.76E+07	7.00E+01	3.14E+06	5.84E+00	4.48E+05	8.34E-01	2.24E+05	4.17E-01	1.60E+05	2.98E-01
7.00E+03	5.60E+08	1.04E+03	3.29E+07	6.13E+01	2.75E+06	5.11E+00	3.92E+05	7.29E-01	1.96E+05	3.65E-01	1.40E+05	2.61E-01
6.00E+03	4.80E+08	8.93E+02	2.82E+07	5.25E+01	2.35E+06	4.38E+00	3.36E+05	6.25E-01	1.68E+05	3.13E-01	1.20E+05	2.23E-01
5.00E+03	4.00E+08	7.44E+02	2.35E+07	4.38E+01	1.96E+06	3.65E+00	2.80E+05	5.21E-01	1.40E+05	2.61E-01	1.00E+05	1.86E-01
4.00E+03	3.20E+08	5.95E+02	1.88E+07	3.50E+01	1.57E+06	2.92E+00	2.24E+05	4.17E-01	1.12E+05	2.08E-01	8.00E+04	1.49E-01
3.00E+03	2.40E+08	4.46E+02	1.41E+07	2.63E+01	1.18E+06	2.19E+00	1.68E+05	3.13E-01	8.40E+04	1.56E-01	6.00E+04	1.12E-01
2.00E+03	1.60E+08	2.98E+02	9.41E+06	1.75E+01	7.84E+05	1.46E+00	1.12E+05	2.08E-01	5.60E+04	1.04E-01	4.00E+04	7.44E-02
1.00E+03	8.00E+07	1.49E+02	4.71E+06	8.75E+00	3.92E+05	7.29E-01	5.60E+04	1.04E-01	2.80E+04	5.21E-02	2.00E+04	3.72E-02
9.00E+02	7.20E+07	1.34E+02	4.24E+06	7.88E+00	3.53E+05	6.57E-01	5.04E+04	9.38E-02	2.52E+04	4.69E-02	1.80E+04	3.35E-02

8.00E+02	6.40E+07	1.19E+02	3.76E+06	7.00E+00	3.14E+05	5.84E-01	4.48E+04	8.34E-02	2.24E+04	4.17E-02	1.60E+04	2.98E-02
7.00E+02	5.60E+07	1.04E+02	3.29E+06	6.13E+00	2.75E+05	5.11E-01	3.92E+04	7.29E-02	1.96E+04	3.65E-02	1.40E+04	2.61E-02
6.00E+02	4.80E+07	8.93E+01	2.82E+06	5.25E+00	2.35E+05	4.38E-01	3.36E+04	6.25E-02	1.68E+04	3.13E-02	1.20E+04	2.23E-02
5.00E+02	4.00E+07	7.44E+01	2.35E+06	4.38E+00	1.96E+05	3.65E-01	2.80E+04	5.21E-02	1.40E+04	2.61E-02	1.00E+04	1.86E-02
4.00E+02	3.20E+07	5.95E+01	1.88E+06	3.50E+00	1.57E+05	2.92E-01	2.24E+04	4.17E-02	1.12E+04	2.08E-02	8.00E+03	1.49E-02
3.00E+02	2.40E+07	4.46E+01	1.41E+06	2.63E+00	1.18E+05	2.19E-01	1.68E+04	3.13E-02	8.40E+03	1.56E-02	6.00E+03	1.12E-02
2.00E+02	1.60E+07	2.98E+01	9.41E+05	1.75E+00	7.84E+04	1.46E-01	1.12E+04	2.08E-02	5.60E+03	1.04E-02	4.00E+03	7.44E-03
1.00E+02	8.00E+06	1.49E+01	4.71E+05	8.75E-01	3.92E+04	7.29E-02	5.60E+03	1.04E-02	2.80E+03	5.21E-03	2.00E+03	3.72E-03
9.00E+01	7.20E+06	1.34E+01	4.24E+05	7.88E-01	3.53E+04	6.57E-02	5.04E+03	9.38E-03	2.52E+03	4.69E-03	1.80E+03	3.35E-03
8.00E+01	6.40E+06	1.19E+01	3.76E+05	7.00E-01	3.14E+04	5.84E-02	4.48E+03	8.34E-03	2.24E+03	4.17E-03	1.60E+03	2.98E-03
7.00E+01	5.60E+06	1.04E+01	3.29E+05	6.13E-01	2.75E+04	5.11E-02	3.92E+03	7.29E-03	1.96E+03	3.65E-03	1.40E+03	2.61E-03
6.00E+01	4.80E+06	8.93E+00	2.82E+05	5.25E-01	2.35E+04	4.38E-02	3.36E+03	6.25E-03	1.68E+03	3.13E-03	1.20E+03	2.23E-03
5.00E+01	4.00E+06	7.44E+00	2.35E+05	4.38E-01	1.96E+04	3.65E-02	2.80E+03	5.21E-03	1.40E+03	2.61E-03	1.00E+03	1.86E-03
4.00E+01	3.20E+06	5.95E+00	1.88E+05	3.50E-01	1.57E+04	2.92E-02	2.24E+03	4.17E-03	1.12E+03	2.08E-03	8.00E+02	1.49E-03
3.00E+01	2.40E+06	4.46E+00	1.41E+05	2.63E-01	1.18E+04	2.19E-02	1.68E+03	3.13E-03	8.40E+02	1.56E-03	6.00E+02	1.12E-03
2.00E+01	1.60E+06	2.98E+00	9.41E+04	1.75E-01	7.84E+03	1.46E-02	1.12E+03	2.08E-03	5.60E+02	1.04E-03	4.00E+02	7.44E-04
1.00E+01	8.00E+05	1.49E+00	4.71E+04	8.75E-02	3.92E+03	7.29E-03	5.60E+02	1.04E-03	2.80E+02	5.21E-04	2.00E+02	3.72E-04
9.00E+00	7.20E+05	1.34E+00	4.24E+04	7.88E-02	3.53E+03	6.57E-03	5.04E+02	9.38E-04	2.52E+02	4.69E-04	1.80E+02	3.35E-04
8.00E+00	6.40E+05	1.19E+00	3.76E+04	7.00E-02	3.14E+03	5.84E-03	4.48E+02	8.34E-04	2.24E+02	4.17E-04	1.60E+02	2.98E-04
7.00E+00	5.60E+05	1.04E+00	3.29E+04	6.13E-02	2.75E+03	5.11E-03	3.92E+02	7.29E-04	1.96E+02	3.65E-04	1.40E+02	2.61E-04
6.00E+00	4.80E+05	8.93E-01	2.82E+04	5.25E-02	2.35E+03	4.38E-03	3.36E+02	6.25E-04	1.68E+02	3.13E-04	1.20E+02	2.23E-04
5.00E+00	4.00E+05	7.44E-01	2.35E+04	4.38E-02	1.96E+03	3.65E-03	2.80E+02	5.21E-04	1.40E+02	2.61E-04	1.00E+02	1.86E-04

Above the RED line is Intermediate Level waste (i.e.>12000 Bq g^{-1} for beta-gamma solid waste)

Below the GREEN line may not be categorised as radioactive waste (i.e. <0.37 Bq g^{-1} for solid waste)

In between these two lines the radioactive material would most likely be categorised as Low Level Waste.

TABLE 5.2a. Continued

2. Based on a solid steel waste item occupying $0.07m^3$, with a $1m^2$ surface area and 50% free space.

Decontamination From Each Recycling Operation

Specify Df For each Pass;

PASS 1 =	17	based on a 1 sq.m surface area
PASS 2 =	12	(Df's corrected upwards slightly to take account of a full media recycles)
PASS 3 =	7	
PASS 4 =	2	
PASS 5 =	1.4	
Total Df =	38	
Mean Df =	8	
Monitor conversion factor =	8	Where 100microSieverts/hr is equivalent to 800Bq/sq.cm for conversion from RO2 to BP3 measurements
Total Sample Area =	10000	sq.cm Assumes a cube with six sides ~41cm sq. (0.40825 m)
Mass of waste (g) =	268800	Assumes 0.07cu.metre volume of steel waste at 7.8te/cu.metre and 50% voidage = 268800g of waste
Initial Trial Media Volume =	25696	cu.cm Link to waste volume sheet(This assumes the worst case coverage see Chapter 4.1-recycling)

Dose Rate	Start Activity	Specific Start	Pass 1	Specific P1	Pass 2	Specific P2	Pass 3	Specific P3	Pass 4	Specific P4	Pass 5	Specific P5
(microSv/hr)	(Bq)	Act'y(Bq/g)	Activity(Bq)	Act'y(Bq/g)	Activity(Bq)	Act'y(Bq/g)	Activity(Bq)	Act'y(Bq/g)	Activity(Bq)	Act'y(Bq/g)	Activity(Bq)	Act'y(Bq/g)
1.00E+07	8.00E+11	2.98E+06	4.71E+10	1.75E+05	3.92E+09	1.46E+04	5.60E+08	2.08E+03	2.80E+08	1.04E+03	2.00E+08	7.44E+02
9.00E+06	7.20E+11	2.68E+06	4.24E+10	1.58E+05	3.53E+09	1.31E+04	5.04E+08	1.88E+03	2.52E+08	9.38E+02	1.80E+08	6.70E+02
8.00E+06	6.40E+11	2.38E+06	3.76E+10	1.40E+05	3.14E+09	1.17E+04	4.48E+08	1.67E+03	2.24E+08	8.34E+02	1.60E+08	5.95E+02
7.00E+06	5.60E+11	2.08E+06	3.29E+10	1.23E+05	2.75E+09	1.02E+04	3.92E+08	1.46E+03	1.96E+08	7.29E+02	1.40E+08	5.21E+02
6.00E+06	4.80E+11	1.79E+06	2.82E+10	1.05E+05	2.35E+09	8.75E+03	3.36E+08	1.25E+03	1.68E+08	6.25E+02	1.20E+08	4.47E+02
5.00E+06	4.00E+11	1.49E+06	2.35E+10	8.75E+04	1.96E+09	7.29E+03	2.80E+08	1.04E+03	1.40E+08	5.21E+02	1.00E+08	3.72E+02
4.70E+06	3.76E+11	1.40E+06	2.21E+10	8.23E+04	1.84E+09	6.86E+03	2.63E+08	9.80E+02	1.32E+08	4.90E+02	9.40E+07	3.50E+02
4.40E+06	3.52E+11	1.31E+06	2.07E+10	7.70E+04	1.73E+09	6.42E+03	2.46E+08	9.17E+02	1.23E+08	4.59E+02	8.80E+07	3.28E+02
4.10E+06	3.28E+11	1.22E+06	1.93E+10	7.18E+04	1.61E+09	5.98E+03	2.30E+08	8.55E+02	1.15E+08	4.27E+02	8.20E+07	3.05E+02
3.80E+06	3.04E+11	1.13E+06	1.79E+10	6.65E+04	1.49E+09	5.54E+03	2.13E+08	7.92E+02	1.06E+08	3.96E+02	7.60E+07	2.83E+02
3.50E+06	2.80E+11	1.04E+06	1.65E+10	6.13E+04	1.37E+09	5.11E+03	1.96E+08	7.29E+02	9.80E+07	3.65E+02	7.00E+07	2.61E+02
3.20E+06	2.56E+11	9.52E+05	1.51E+10	5.60E+04	1.25E+09	4.67E+03	1.79E+08	6.67E+02	8.96E+07	3.33E+02	6.40E+07	2.38E+02
2.90E+06	2.32E+11	8.63E+05	1.36E+10	5.08E+04	1.14E+09	4.23E+03	1.62E+08	6.04E+02	8.12E+07	3.02E+02	5.80E+07	2.16E+02
2.60E+06	2.08E+11	7.74E+05	1.22E+10	4.55E+04	1.02E+09	3.79E+03	1.46E+08	5.42E+02	7.28E+07	2.71E+02	5.20E+07	1.94E+02
2.30E+06	1.84E+11	6.85E+05	1.08E+10	4.03E+04	9.02E+08	3.36E+03	1.29E+08	4.79E+02	6.44E+07	2.40E+02	4.60E+07	1.71E+02
2.00E+06	1.60E+11	5.95E+05	9.41E+09	3.50E+04	7.84E+08	2.92E+03	1.12E+08	4.17E+02	5.60E+07	2.08E+02	4.00E+07	1.49E+02
1.80E+06	1.44E+11	5.36E+05	8.47E+09	3.15E+04	7.06E+08	2.63E+03	1.01E+08	3.75E+02	5.04E+07	1.88E+02	3.60E+07	1.34E+02
1.60E+06	1.28E+11	4.76E+05	7.53E+09	2.80E+04	6.27E+08	2.33E+03	8.96E+07	3.33E+02	4.48E+07	1.67E+02	3.20E+07	1.19E+02
1.40E+06	1.12E+11	4.17E+05	6.59E+09	2.45E+04	5.49E+08	2.04E+03	7.84E+07	2.92E+02	3.92E+07	1.46E+02	2.80E+07	1.04E+02
1.20E+06	9.60E+10	3.57E+05	5.65E+09	2.10E+04	4.71E+08	1.75E+03	6.72E+07	2.50E+02	3.36E+07	1.25E+02	2.40E+07	8.93E+01
1.00E+06	8.00E+10	2.98E+05	4.71E+09	1.75E+04	3.92E+08	1.46E+03	5.60E+07	2.08E+02	2.80E+07	1.04E+02	2.00E+07	7.44E+01
9.00E+05	7.20E+10	2.68E+05	4.24E+09	1.58E+04	3.53E+08	1.31E+03	5.04E+07	1.88E+02	2.52E+07	9.38E+01	1.80E+07	6.70E+01
8.00E+05	6.40E+10	2.38E+05	3.76E+09	1.40E+04	3.14E+08	1.17E+03	4.48E+07	1.67E+02	2.24E+07	8.34E+01	1.60E+07	5.95E+01

7.00E+05	5.60E+10	2.08E+05	3.29E+09	1.23E+04	2.75E+08	1.02E+03	3.92E+07	1.46E+02	1.96E+07	7.29E+01	1.40E+07	5.21E+01
6.00E+05	4.80E+10	1.79E+05	2.82E+09	1.05E+04	2.35E+08	8.75E+02	3.36E+07	1.25E+02	1.68E+07	6.25E+01	1.20E+07	4.47E+01
5.00E+05	4.00E+10	1.49E+05	2.35E+09	8.75E+03	1.96E+08	7.29E+02	2.80E+07	1.04E+02	1.40E+07	5.21E+01	1.00E+07	3.72E+01
4.50E+05	3.60E+10	1.34E+05	2.12E+09	7.88E+03	1.76E+08	6.57E+02	2.52E+07	9.38E+01	1.26E+07	4.69E+01	9.00E+06	3.35E+01
4.00E+05	3.20E+10	1.19E+05	1.88E+09	7.00E+03	1.57E+08	5.84E+02	2.24E+07	8.34E+01	1.12E+07	4.17E+01	8.00E+06	2.98E+01
3.50E+05	2.80E+10	1.04E+05	1.65E+09	6.13E+03	1.37E+08	5.11E+02	1.96E+07	7.29E+01	9.80E+06	3.65E+01	7.00E+06	2.61E+01
3.00E+05	2.40E+10	8.93E+04	1.41E+09	5.25E+03	1.18E+08	4.38E+02	1.68E+07	6.25E+01	8.40E+06	3.13E+01	6.00E+06	2.23E+01
2.50E+05	2.00E+10	7.44E+04	1.18E+09	4.38E+03	9.80E+07	3.65E+02	1.40E+07	5.21E+01	7.00E+06	2.61E+01	5.00E+06	1.86E+01
2.00E+05	1.60E+10	5.95E+04	9.41E+08	3.50E+03	7.84E+07	2.92E+02	1.12E+07	4.17E+01	5.60E+06	2.08E+01	4.00E+06	1.49E+01
1.80E+05	1.44E+10	5.36E+04	8.47E+08	3.15E+03	7.06E+07	2.63E+02	1.01E+07	3.75E+01	5.04E+06	1.88E+01	3.60E+06	1.34E+01
1.60E+05	1.28E+10	4.76E+04	7.53E+08	2.80E+03	6.27E+07	2.33E+02	8.96E+06	3.33E+01	4.48E+06	1.67E+01	3.20E+06	1.19E+01
1.40E+05	1.12E+10	4.17E+04	6.59E+08	2.45E+03	5.49E+07	2.04E+02	7.84E+06	2.92E+01	3.92E+06	1.46E+01	2.80E+06	1.04E+01
1.20E+05	9.60E+09	3.57E+04	5.65E+08	2.10E+03	4.71E+07	1.75E+02	6.72E+06	2.50E+01	3.36E+06	1.25E+01	2.40E+06	8.93E+00
1.00E+05	8.00E+09	2.98E+04	4.71E+08	1.75E+03	3.92E+07	1.46E+02	5.60E+06	2.08E+01	2.80E+06	1.04E+01	2.00E+06	7.44E+00
9.00E+04	7.20E+09	2.68E+04	4.24E+08	1.58E+03	3.53E+07	1.31E+02	5.04E+06	1.88E+01	2.52E+06	9.38E+00	1.80E+06	6.70E+00
8.00E+04	6.40E+09	2.38E+04	3.76E+08	1.40E+03	3.14E+07	1.17E+02	4.48E+06	1.67E+01	2.24E+06	8.34E+00	1.60E+06	5.95E+00
7.00E+04	5.60E+09	2.08E+04	3.29E+08	1.23E+03	2.75E+07	1.02E+02	3.92E+06	1.46E+01	1.96E+06	7.29E+00	1.40E+06	5.21E+00
6.00E+04	4.80E+09	1.79E+04	2.82E+08	1.05E+03	2.35E+07	8.75E+01	3.36E+06	1.25E+01	1.68E+06	6.25E+00	1.20E+06	4.47E+00
5.00E+04	4.00E+09	1.49E+04	2.35E+08	8.75E+02	1.96E+07	7.29E+01	2.80E+06	1.04E+01	1.40E+06	5.21E+00	1.00E+06	3.72E+00
4.50E+04	3.60E+09	1.34E+04	2.12E+08	7.88E+02	1.76E+07	6.57E+01	2.52E+06	9.38E+00	1.26E+06	4.69E+00	9.00E+05	3.35E+00
4.00E+04	3.20E+09	1.19E+04	1.88E+08	7.00E+02	1.57E+07	5.84E+01	2.24E+06	8.34E+00	1.12E+06	4.17E+00	8.00E+05	2.98E+00
3.50E+04	2.80E+09	1.04E+04	1.65E+08	6.13E+02	1.37E+07	5.11E+01	1.96E+06	7.29E+00	9.80E+05	3.65E+00	7.00E+05	2.61E+00
3.00E+04	2.40E+09	8.93E+03	1.41E+08	5.25E+02	1.18E+07	4.38E+01	1.68E+06	6.25E+00	8.40E+05	3.13E+00	6.00E+05	2.23E+00
2.50E+04	2.00E+09	7.44E+03	1.18E+08	4.38E+02	9.80E+06	3.65E+01	1.40E+06	5.21E+00	7.00E+05	2.61E+00	5.00E+05	1.86E+00
2.00E+04	1.60E+09	5.95E+03	9.41E+07	3.50E+02	7.84E+06	2.92E+01	1.12E+06	4.17E+00	5.60E+05	2.08E+00	4.00E+05	1.49E+00
1.50E+04	1.20E+09	4.46E+03	7.06E+07	2.63E+02	5.88E+06	2.19E+01	8.40E+05	3.13E+00	4.20E+05	1.56E+00	3.00E+05	1.12E+00
1.00E+04	8.00E+08	2.98E+03	4.71E+07	1.75E+02	3.92E+06	1.46E+01	5.60E+05	2.08E+00	2.80E+05	1.04E+00	2.00E+05	7.44E-01
9.00E+03	7.20E+08	2.68E+03	4.24E+07	1.58E+02	3.53E+06	1.31E+01	5.04E+05	1.88E+00	2.52E+05	9.38E-01	1.80E+05	6.70E-01
8.00E+03	6.40E+08	2.38E+03	3.76E+07	1.40E+02	3.14E+06	1.17E+01	4.48E+05	1.67E+00	2.24E+05	8.34E-01	1.60E+05	5.95E-01
7.00E+03	5.60E+08	2.08E+03	3.29E+07	1.23E+02	2.75E+06	1.02E+01	3.92E+05	1.46E+00	1.96E+05	7.29E-01	1.40E+05	5.21E-01
6.00E+03	4.80E+08	1.79E+03	2.82E+07	1.05E+02	2.35E+06	8.75E+00	3.36E+05	1.25E+00	1.68E+05	6.25E-01	1.20E+05	4.47E-01
5.00E+03	4.00E+08	1.49E+03	2.35E+07	8.75E+01	1.96E+06	7.29E+00	2.80E+05	1.04E+00	1.40E+05	5.21E-01	1.00E+05	3.72E-01
4.00E+03	3.20E+08	1.19E+03	1.88E+07	7.00E+01	1.57E+06	5.84E+00	2.24E+05	8.34E-01	1.12E+05	4.17E-01	8.00E+04	2.98E-01
3.00E+03	2.40E+08	8.93E+02	1.41E+07	5.25E+01	1.18E+06	4.38E+00	1.68E+05	6.25E-01	8.40E+04	3.13E-01	6.00E+04	2.23E-01
2.00E+03	1.60E+08	5.95E+02	9.41E+06	3.50E+01	7.84E+05	2.92E+00	1.12E+05	4.17E-01	5.60E+04	2.08E-01	4.00E+04	1.49E-01
1.00E+03	8.00E+07	2.98E+02	4.71E+06	1.75E+01	3.92E+05	1.46E+00	5.60E+04	2.08E-01	2.80E+04	1.04E-01	2.00E+04	7.44E-02
9.00E+02	7.20E+07	2.68E+02	4.24E+06	1.58E+01	3.53E+05	1.31E+00	5.04E+04	1.88E-01	2.52E+04	9.38E-02	1.80E+04	6.70E-02
8.00E+02	6.40E+07	2.38E+02	3.76E+06	1.40E+01	3.14E+05	1.17E+00	4.48E+04	1.67E-01	2.24E+04	8.34E-02	1.60E+04	5.95E-02
7.00E+02	5.60E+07	2.08E+02	3.29E+06	1.23E+01	2.75E+05	1.02E+00	3.92E+04	1.46E-01	1.96E+04	7.29E-02	1.40E+04	5.21E-02
6.00E+02	4.80E+07	1.79E+02	2.82E+06	1.05E+01	2.35E+05	8.75E-01	3.36E+04	1.25E-01	1.68E+04	6.25E-02	1.20E+04	4.47E-02
5.00E+02	4.00E+07	1.49E+02	2.35E+06	8.75E+00	1.96E+05	7.29E-01	2.80E+04	1.04E-01	1.40E+04	5.21E-02	1.00E+04	3.72E-02
4.00E+02	3.20E+07	1.19E+02	1.88E+06	7.00E+00	1.57E+05	5.84E-01	2.24E+04	8.34E-02	1.12E+04	4.17E-02	8.00E+03	2.98E-02
3.00E+02	2.40E+07	8.93E+01	1.41E+06	5.25E+00	1.18E+05	4.38E-01	1.68E+04	6.25E-02	8.40E+03	3.13E-02	6.00E+03	2.23E-02

2.00E+02	1.60E+07	5.95E+01	9.41E+05	3.50E+00	7.84E+04	2.92E-01	1.12E+04	4.17E-02	5.60E+03	2.08E-02	4.00E+03	1.49E-02
1.00E+02	8.00E+06	2.98E+01	4.71E+05	1.75E+00	3.92E+04	1.46E-01	5.60E+03	2.08E-02	2.80E+03	1.04E-02	2.00E+03	7.44E-03
9.00E+01	7.20E+06	2.68E+01	4.24E+05	1.58E+00	3.53E+04	1.31E-01	5.04E+03	1.88E-02	2.52E+03	9.38E-03	1.80E+03	6.70E-03
8.00E+01	6.40E+06	2.38E+01	3.76E+05	1.40E+00	3.14E+04	1.17E-01	4.48E+03	1.67E-02	2.24E+03	8.34E-03	1.60E+03	5.95E-03
7.00E+01	5.60E+06	2.08E+01	3.29E+05	1.23E+00	2.75E+04	1.02E-01	3.92E+03	1.46E-02	1.96E+03	7.29E-03	1.40E+03	5.21E-03
6.00E+01	4.80E+06	1.79E+01	2.82E+05	1.05E+00	2.35E+04	8.75E-02	3.36E+03	1.25E-02	1.68E+03	6.25E-03	1.20E+03	4.47E-03
5.00E+01	4.00E+06	1.49E+01	2.35E+05	8.75E-01	1.96E+04	7.29E-02	2.80E+03	1.04E-02	1.40E+03	5.21E-03	1.00E+03	3.72E-03
4.00E+01	3.20E+06	1.19E+01	1.88E+05	7.00E-01	1.57E+04	5.84E-02	2.24E+03	8.34E-03	1.12E+03	4.17E-03	8.00E+02	2.98E-03
3.00E+01	2.40E+06	8.93E+00	1.41E+05	5.25E-01	1.18E+04	4.38E-02	1.68E+03	6.25E-03	8.40E+02	3.13E-03	6.00E+02	2.23E-03
2.00E+01	1.60E+06	5.95E+00	9.41E+04	3.50E-01	7.84E+03	2.92E-02	1.12E+03	4.17E-03	5.60E+02	2.08E-03	4.00E+02	1.49E-03
1.00E+01	8.00E+05	2.98E+00	4.71E+04	1.75E-01	3.92E+03	1.46E-02	5.60E+02	2.08E-03	2.80E+02	1.04E-03	2.00E+02	7.44E-04
9.00E+00	7.20E+05	2.68E+00	4.24E+04	1.58E-01	3.53E+03	1.31E-02	5.04E+02	1.88E-03	2.52E+02	9.38E-04	1.80E+02	6.70E-04
8.00E+00	6.40E+05	2.38E+00	3.76E+04	1.40E-01	3.14E+03	1.17E-02	4.48E+02	1.67E-03	2.24E+02	8.34E-04	1.60E+02	5.95E-04
7.00E+00	5.60E+05	2.08E+00	3.29E+04	1.23E-01	2.75E+03	1.02E-02	3.92E+02	1.46E-03	1.96E+02	7.29E-04	1.40E+02	5.21E-04
6.00E+00	4.80E+05	1.79E+00	2.82E+04	1.05E-01	2.35E+03	8.75E-03	3.36E+02	1.25E-03	1.68E+02	6.25E-04	1.20E+02	4.47E-04
5.00E+00	4.00E+05	1.49E+00	2.35E+04	8.75E-02	1.96E+03	7.29E-03	2.80E+02	1.04E-03	1.40E+02	5.21E-04	1.00E+02	3.72E-04

Above the RED line is Intermediate Level waste (i.e.>12000 Bq g^{-1} for beta-gamma solid waste)

Below the GREEN line may not be categorised as radioactive waste (i.e. <0.37 Bq g^{-1} for solid waste)

In between these two lines the radioactive material would most likely be categorised as Low Level Waste.

TABLE 5.2a. Continued

3. Based on a solid steel waste item occupying $0.07m^3$, with a $1m^2$ surface area and 75% free space.

Decontamination From Each Recycling Operation

Specify Df For each Pass;	PASS 1 =	17	based on a 1 sq.m surface area
	PASS 2 =	12	(Df's corrected upwards slightly to take account of a full media recycles)
	PASS 3 =	7	
	PASS 4 =	2	
	PASS 5 =	1.4	
	Total Df =	38	
	Mean Df =	8	
	Monitor conversion factor =	8	Where 100microSieverts/hr is equivalent to 800Bq/sq.cm for conversion from RO2 to BP3 measurements
	Total Sample Area =	10000	sq.cm Assumes a cube with six sides ~41cm sq. (0.40825 m)
	Mass of waste (g) =	134400	Assumes 0.07cu.metre volume of steel waste at 7.8te/cu.metre and 75% voidage = 134400g of waste
	Initial Trial Media Volume =	25696	cu.cm Link to waste volume sheet(This assumes the worst case coverage see Chapter 4.1-recycling)

Dose Rate (microSv/hr)	Start Activity (Bq)	Specific Start Act'y(Bq/g)	Pass 1 Activity(Bq)	Specific P1 Act'y(Bq/g)	Pass 2 Activity(Bq)	Specific P2 Act'y(Bq/g)	Pass 3 Activity(Bq)	Specific P3 Act'y(Bq/g)	Pass 4 Activity(Bq)	Specific P4 Act'y(Bq/g)	Pass 5 Activity(Bq)	Specific P5 Act'y(Bq/g)
1.00E+07	8.00E+11	5.95E+06	4.71E+10	3.50E+05	3.92E+09	2.92E+04	5.60E+08	4.17E+03	2.80E+08	2.08E+03	2.00E+08	1.49E+03
9.00E+06	7.20E+11	5.36E+06	4.24E+10	3.15E+05	3.53E+09	2.63E+04	5.04E+08	3.75E+03	2.52E+08	1.88E+03	1.80E+08	1.34E+03
8.00E+06	6.40E+11	4.76E+06	3.76E+10	2.80E+05	3.14E+09	2.33E+04	4.48E+08	3.33E+03	2.24E+08	1.67E+03	1.60E+08	1.19E+03
7.00E+06	5.60E+11	4.17E+06	3.29E+10	2.45E+05	2.75E+09	2.04E+04	3.92E+08	2.92E+03	1.96E+08	1.46E+03	1.40E+08	1.04E+03
6.00E+06	4.80E+11	3.57E+06	2.82E+10	2.10E+05	2.35E+09	1.75E+04	3.36E+08	2.50E+03	1.68E+08	1.25E+03	1.20E+08	8.93E+02
5.00E+06	4.00E+11	2.98E+06	2.35E+10	1.75E+05	1.96E+09	1.46E+04	2.80E+08	2.08E+03	1.40E+08	1.04E+03	1.00E+08	7.44E+02
4.70E+06	3.76E+11	2.80E+06	2.21E+10	1.65E+05	1.84E+09	1.37E+04	2.63E+08	1.96E+03	1.32E+08	9.80E+02	9.40E+07	7.00E+02
4.40E+06	3.52E+11	2.62E+06	2.07E+10	1.54E+05	1.73E+09	1.28E+04	2.46E+08	1.83E+03	1.23E+08	9.17E+02	8.80E+07	6.55E+02
4.10E+06	3.28E+11	2.44E+06	1.93E+10	1.44E+05	1.61E+09	1.20E+04	2.30E+08	1.71E+03	1.15E+08	8.55E+02	8.20E+07	6.10E+02
3.80E+06	3.04E+11	2.26E+06	1.79E+10	1.33E+05	1.49E+09	1.11E+04	2.13E+08	1.58E+03	1.06E+08	7.92E+02	7.60E+07	5.66E+02
3.50E+06	2.80E+11	2.08E+06	1.65E+10	1.23E+05	1.37E+09	1.02E+04	1.96E+08	1.46E+03	9.80E+07	7.29E+02	7.00E+07	5.21E+02
3.20E+06	2.56E+11	1.90E+06	1.51E+10	1.12E+05	1.25E+09	9.34E+03	1.79E+08	1.33E+03	8.96E+07	6.67E+02	6.40E+07	4.76E+02
2.90E+06	2.32E+11	1.73E+06	1.36E+10	1.02E+05	1.14E+09	8.46E+03	1.62E+08	1.21E+03	8.12E+07	6.04E+02	5.80E+07	4.32E+02
2.60E+06	2.08E+11	1.55E+06	1.22E+10	9.10E+04	1.02E+09	7.59E+03	1.46E+08	1.08E+03	7.28E+07	5.42E+02	5.20E+07	3.87E+02
2.30E+06	1.84E+11	1.37E+06	1.08E+10	8.05E+04	9.02E+08	6.71E+03	1.29E+08	9.59E+02	6.44E+07	4.79E+02	4.60E+07	3.42E+02
2.00E+06	1.60E+11	1.19E+06	9.41E+09	7.00E+04	7.84E+08	5.84E+03	1.12E+08	8.34E+02	5.60E+07	4.17E+02	4.00E+07	2.98E+02
1.80E+06	1.44E+11	1.07E+06	8.47E+09	6.30E+04	7.06E+08	5.25E+03	1.01E+08	7.50E+02	5.04E+07	3.75E+02	3.60E+07	2.68E+02
1.60E+06	1.28E+11	9.52E+05	7.53E+09	5.60E+04	6.27E+08	4.67E+03	8.96E+07	6.67E+02	4.48E+07	3.33E+02	3.20E+07	2.38E+02
1.40E+06	1.12E+11	8.33E+05	6.59E+09	4.90E+04	5.49E+08	4.08E+03	7.84E+07	5.84E+02	3.92E+07	2.92E+02	2.80E+07	2.08E+02
1.20E+06	9.60E+10	7.14E+05	5.65E+09	4.20E+04	4.71E+08	3.50E+03	6.72E+07	5.00E+02	3.36E+07	2.50E+02	2.40E+07	1.79E+02
1.00E+06	8.00E+10	5.95E+05	4.71E+09	3.50E+04	3.92E+08	2.92E+03	5.60E+07	4.17E+02	2.80E+07	2.08E+02	2.00E+07	1.49E+02
9.00E+05	7.20E+10	5.36E+05	4.24E+09	3.15E+04	3.53E+08	2.63E+03	5.04E+07	3.75E+02	2.52E+07	1.88E+02	1.80E+07	1.34E+02

8.00E+05	6.40E+10	4.76E+05	3.76E+09	2.80E+04	3.14E+08	2.33E+03	4.48E+07	3.33E+02	2.24E+07	1.67E+02	1.60E+07	1.19E+02
7.00E+05	5.60E+10	4.17E+05	3.29E+09	2.45E+04	2.75E+08	2.04E+03	3.92E+07	2.92E+02	1.96E+07	1.46E+02	1.40E+07	1.04E+02
6.00E+05	4.80E+10	3.57E+05	2.82E+09	2.10E+04	2.35E+08	1.75E+03	3.36E+07	2.50E+02	1.68E+07	1.25E+02	1.20E+07	8.93E+01
5.00E+05	4.00E+10	2.98E+05	2.35E+09	1.75E+04	1.96E+08	1.46E+03	2.80E+07	2.08E+02	1.40E+07	1.04E+02	1.00E+07	7.44E+01
4.50E+05	3.60E+10	2.68E+05	2.12E+09	1.58E+04	1.76E+08	1.31E+03	2.52E+07	1.88E+02	1.26E+07	9.38E+01	9.00E+06	6.70E+01
4.00E+05	3.20E+10	2.38E+05	1.88E+09	1.40E+04	1.57E+08	1.17E+03	2.24E+07	1.67E+02	1.12E+07	8.34E+01	8.00E+06	5.95E+01
3.50E+05	2.80E+10	2.08E+05	1.65E+09	1.23E+04	1.37E+08	1.02E+03	1.96E+07	1.46E+02	9.80E+06	7.29E+01	7.00E+06	5.21E+01
3.00E+05	2.40E+10	1.79E+05	1.41E+09	1.05E+04	1.18E+08	8.75E+02	1.68E+07	1.25E+02	8.40E+06	6.25E+01	6.00E+06	4.47E+01
2.50E+05	2.00E+10	1.49E+05	1.18E+09	8.75E+03	9.80E+07	7.29E+02	1.40E+07	1.04E+02	7.00E+06	5.21E+01	5.00E+06	3.72E+01
2.00E+05	1.60E+10	1.19E+05	9.41E+08	7.00E+03	7.84E+07	5.84E+02	1.12E+07	8.34E+01	5.60E+06	4.17E+01	4.00E+06	2.98E+01
1.80E+05	1.44E+10	1.07E+05	8.47E+08	6.30E+03	7.06E+07	5.25E+02	1.01E+07	7.50E+01	5.04E+06	3.75E+01	3.60E+06	2.68E+01
1.60E+05	1.28E+10	9.52E+04	7.53E+08	5.60E+03	6.27E+07	4.67E+02	8.96E+06	6.67E+01	4.48E+06	3.33E+01	3.20E+06	2.38E+01
1.40E+05	1.12E+10	8.33E+04	6.59E+08	4.90E+03	5.49E+07	4.08E+02	7.84E+06	5.84E+01	3.92E+06	2.92E+01	2.80E+06	2.08E+01
1.20E+05	9.60E+09	7.14E+04	5.65E+08	4.20E+03	4.71E+07	3.50E+02	6.72E+06	5.00E+01	3.36E+06	2.50E+01	2.40E+06	1.79E+01
1.00E+05	8.00E+09	5.95E+04	4.71E+08	3.50E+03	3.92E+07	2.92E+02	5.60E+06	4.17E+01	2.80E+06	2.08E+01	2.00E+06	1.49E+01
9.00E+04	7.20E+09	5.36E+04	4.24E+08	3.15E+03	3.53E+07	2.63E+02	5.04E+06	3.75E+01	2.52E+06	1.88E+01	1.80E+06	1.34E+01
8.00E+04	6.40E+09	4.76E+04	3.76E+08	2.80E+03	3.14E+07	2.33E+02	4.48E+06	3.33E+01	2.24E+06	1.67E+01	1.60E+06	1.19E+01
7.00E+04	5.60E+09	4.17E+04	3.29E+08	2.45E+03	2.75E+07	2.04E+02	3.92E+06	2.92E+01	1.96E+06	1.46E+01	1.40E+06	1.04E+01
6.00E+04	4.80E+09	3.57E+04	2.82E+08	2.10E+03	2.35E+07	1.75E+02	3.36E+06	2.50E+01	1.68E+06	1.25E+01	1.20E+06	8.93E+00
5.00E+04	4.00E+09	2.98E+04	2.35E+08	1.75E+03	1.96E+07	1.46E+02	2.80E+06	2.08E+01	1.40E+06	1.04E+01	1.00E+06	7.44E+00
4.50E+04	3.60E+09	2.68E+04	2.12E+08	1.58E+03	1.76E+07	1.31E+02	2.52E+06	1.88E+01	1.26E+06	9.38E+00	9.00E+05	6.70E+00
4.00E+04	3.20E+09	2.38E+04	1.88E+08	1.40E+03	1.57E+07	1.17E+02	2.24E+06	1.67E+01	1.12E+06	8.34E+00	8.00E+05	5.95E+00
3.50E+04	2.80E+09	2.08E+04	1.65E+08	1.23E+03	1.37E+07	1.02E+02	1.96E+06	1.46E+01	9.80E+05	7.29E+00	7.00E+05	5.21E+00
3.00E+04	2.40E+09	1.79E+04	1.41E+08	1.05E+03	1.18E+07	8.75E+01	1.68E+06	1.25E+01	8.40E+05	6.25E+00	6.00E+05	4.47E+00
2.50E+04	2.00E+09	1.49E+04	1.18E+08	8.75E+02	9.80E+06	7.29E+01	1.40E+06	1.04E+01	7.00E+05	5.21E+00	5.00E+05	3.72E+00
2.00E+04	1.60E+09	1.19E+04	9.41E+07	7.00E+02	7.84E+06	5.84E+01	1.12E+06	8.34E+00	5.60E+05	4.17E+00	4.00E+05	2.98E+00
1.50E+04	1.20E+09	8.93E+03	7.06E+07	5.25E+02	5.88E+06	4.38E+01	8.40E+05	6.25E+00	4.20E+05	3.13E+00	3.00E+05	2.23E+00
1.00E+04	8.00E+08	5.95E+03	4.71E+07	3.50E+02	3.92E+06	2.92E+01	5.60E+05	4.17E+00	2.80E+05	2.08E+00	2.00E+05	1.49E+00
9.00E+03	7.20E+08	5.36E+03	4.24E+07	3.15E+02	3.53E+06	2.63E+01	5.04E+05	3.75E+00	2.52E+05	1.88E+00	1.80E+05	1.34E+00
8.00E+03	6.40E+08	4.76E+03	3.76E+07	2.80E+02	3.14E+06	2.33E+01	4.48E+05	3.33E+00	2.24E+05	1.67E+00	1.60E+05	1.19E+00
7.00E+03	5.60E+08	4.17E+03	3.29E+07	2.45E+02	2.75E+06	2.04E+01	3.92E+05	2.92E+00	1.96E+05	1.46E+00	1.40E+05	1.04E+00
6.00E+03	4.80E+08	3.57E+03	2.82E+07	2.10E+02	2.35E+06	1.75E+01	3.36E+05	2.50E+00	1.68E+05	1.25E+00	1.20E+05	8.93E-01
5.00E+03	4.00E+08	2.98E+03	2.35E+07	1.75E+02	1.96E+06	1.46E+01	2.80E+05	2.08E+00	1.40E+05	1.04E+00	1.00E+05	7.44E-01
4.00E+03	3.20E+08	2.38E+03	1.88E+07	1.40E+02	1.57E+06	1.17E+01	2.24E+05	1.67E+00	1.12E+05	8.34E-01	8.00E+04	5.95E-01
3.00E+03	2.40E+08	1.79E+03	1.41E+07	1.05E+02	1.18E+06	8.75E+00	1.68E+05	1.25E+00	8.40E+04	6.25E-01	6.00E+04	4.47E-01
2.00E+03	1.60E+08	1.19E+03	9.41E+06	7.00E+01	7.84E+05	5.84E+00	1.12E+05	8.34E-01	5.60E+04	4.17E-01	4.00E+04	2.98E-01
1.00E+03	8.00E+07	5.95E+02	4.71E+06	3.50E+01	3.92E+05	2.92E+00	5.60E+04	4.17E-01	2.80E+04	2.08E-01	2.00E+04	1.49E-01
9.00E+02	7.20E+07	5.36E+02	4.24E+06	3.15E+01	3.53E+05	2.63E+00	5.04E+04	3.75E-01	2.52E+04	1.88E-01	1.80E+04	1.34E-01
8.00E+02	6.40E+07	4.76E+02	3.76E+06	2.80E+01	3.14E+05	2.33E+00	4.48E+04	3.33E-01	2.24E+04	1.67E-01	1.60E+04	1.19E-01
7.00E+02	5.60E+07	4.17E+02	3.29E+06	2.45E+01	2.75E+05	2.04E+00	3.92E+04	2.92E-01	1.96E+04	1.46E-01	1.40E+04	1.04E-01
6.00E+02	4.80E+07	3.57E+02	2.82E+06	2.10E+01	2.35E+05	1.75E+00	3.36E+04	2.50E-01	1.68E+04	1.25E-01	1.20E+04	8.93E-02
5.00E+02	4.00E+07	2.98E+02	2.35E+06	1.75E+01	1.96E+05	1.46E+00	2.80E+04	2.08E-01	1.40E+04	1.04E-01	1.00E+04	7.44E-02
4.00E+02	3.20E+07	2.38E+02	1.88E+06	1.40E+01	1.57E+05	1.17E+00	2.24E+04	1.67E-01	1.12E+04	8.34E-02	8.00E+03	5.95E-02

3.00E+02	2.40E+07	1.79E+02	1.41E+06	1.05E+01	1.18E+05	8.75E-01	1.68E+04	1.25E-01	8.40E+03	6.25E-02	6.00E+03	4.47E-02
2.00E+02	1.60E+07	1.19E+02	9.41E+05	7.00E+00	7.84E+04	5.84E-01	1.12E+04	8.34E-02	5.60E+03	4.17E-02	4.00E+03	2.98E-02
1.00E+02	8.00E+06	5.95E+01	4.71E+05	3.50E+00	3.92E+04	2.92E-01	5.60E+03	4.17E-02	2.80E+03	2.08E-02	2.00E+03	1.49E-02
9.00E+01	7.20E+06	5.36E+01	4.24E+05	3.15E+00	3.53E+04	2.63E-01	5.04E+03	3.75E-02	2.52E+03	1.88E-02	1.80E+03	1.34E-02
8.00E+01	6.40E+06	4.76E+01	3.76E+05	2.80E+00	3.14E+04	2.33E-01	4.48E+03	3.33E-02	2.24E+03	1.67E-02	1.60E+03	1.19E-02
7.00E+01	5.60E+06	4.17E+01	3.29E+05	2.45E+00	2.75E+04	2.04E-01	3.92E+03	2.92E-02	1.96E+03	1.46E-02	1.40E+03	1.04E-02
6.00E+01	4.80E+06	3.57E+01	2.82E+05	2.10E+00	2.35E+04	1.75E-01	3.36E+03	2.50E-02	1.68E+03	1.25E-02	1.20E+03	8.93E-03
5.00E+01	4.00E+06	2.98E+01	2.35E+05	1.75E+00	1.96E+04	1.46E-01	2.80E+03	2.08E-02	1.40E+03	1.04E-02	1.00E+03	7.44E-03
4.00E+01	3.20E+06	2.38E+01	1.88E+05	1.40E+00	1.57E+04	1.17E-01	2.24E+03	1.67E-02	1.12E+03	8.34E-03	8.00E+02	5.95E-03
3.00E+01	2.40E+06	1.79E+01	1.41E+05	1.05E+00	1.18E+04	8.75E-02	1.68E+03	1.25E-02	8.40E+02	6.25E-03	6.00E+02	4.47E-03
2.00E+01	1.60E+06	1.19E+01	9.41E+04	7.00E-01	7.84E+03	5.84E-02	1.12E+03	8.34E-03	5.60E+02	4.17E-03	4.00E+02	2.98E-03
1.00E+01	8.00E+05	5.95E+00	4.71E+04	3.50E-01	3.92E+03	2.92E-02	5.60E+02	4.17E-03	2.80E+02	2.08E-03	2.00E+02	1.49E-03
9.00E+00	7.20E+05	5.36E+00	4.24E+04	3.15E-01	3.53E+03	2.63E-02	5.04E+02	3.75E-03	2.52E+02	1.88E-03	1.80E+02	1.34E-03
8.00E+00	6.40E+05	4.76E+00	3.76E+04	2.80E-01	3.14E+03	2.33E-02	4.48E+02	3.33E-03	2.24E+02	1.67E-03	1.60E+02	1.19E-03
7.00E+00	5.60E+05	4.17E+00	3.29E+04	2.45E-01	2.75E+03	2.04E-02	3.92E+02	2.92E-03	1.96E+02	1.46E-03	1.40E+02	1.04E-03
6.00E+00	4.80E+05	3.57E+00	2.82E+04	2.10E-01	2.35E+03	1.75E-02	3.36E+02	2.50E-03	1.68E+02	1.25E-03	1.20E+02	8.93E-04
5.00E+00	4.00E+05	2.98E+00	2.35E+04	1.75E-01	1.96E+03	1.46E-02	2.80E+02	2.08E-03	1.40E+02	1.04E-03	1.00E+02	7.44E-04

Above the RED line is Intermediate Level waste (i.e.>12000 Bq g^{-1} for beta-gamma solid waste)

Below the GREEN line may not be categorised as radioactive waste (i.e. <0.37 Bq g^{-1} for solid waste)

In between these two lines the radioactive material would most likely be categorised as Low Level Waste.

TABLE 5.2a. Continued

4. Based on a solid steel waste item occupying $0.07m^3$, with a $1m^2$ surface area and 85% free space.

Decontamination From Each Recycling Operation

Specify Df For each Pass;

PASS 1 =	17	based on a 1 sq.m surface area
PASS 2 =	12	(Df's corrected upwards slightly to take account of a full media recycles)
PASS 3 =	7	
PASS 4 =	2	
PASS 5 =	1.4	
Total Df =	38	
Mean Df =	8	
Monitor conversion factor =	8	Where 100microSieverts/hr is equivalent to 800Bq/sq.cm for conversion from RO2 to BP3 measurements
Total Sample Area =	10000	sq.cm Assumes a cube with six sides ~41cm sq. (0.40825 m)
Mass of waste (g) =	80640	Assumes 0.07cu.metre volume of steel waste at 7.8te/cu.metre and 85% voidage = 80640g of waste
Initial Trial Media Volume =	25696	cu.cm Link to waste volume sheet(This assumes the worst case coverage see Chapter 4.1-recycling)

Dose Rate	Start Activity	Specific Start	Pass 1	Specific P1	Pass 2	Specific P2	Pass 3	Specific P3	Pass 4	Specific P4	Pass 5	Specific P5
(microSv/hr)	(Bq)	Act'y(Bq/g)	Activity(Bq)	Act'y(Bq/g)	Activity(Bq)	Act'y(Bq/g)	Activity(Bq)	Act'y(Bq/g)	Activity(Bq)	Act'y(Bq/g)	Activity(Bq)	Act'y(Bq/g)
1.00E+07	8.00E+11	9.92E+06	4.71E+10	5.84E+05	3.92E+09	4.86E+04	5.60E+08	6.95E+03	2.80E+08	3.47E+03	2.00E+08	2.48E+03
9.00E+06	7.20E+11	8.93E+06	4.24E+10	5.25E+05	3.53E+09	4.38E+04	5.04E+08	6.25E+03	2.52E+08	3.13E+03	1.80E+08	2.23E+03
8.00E+06	6.40E+11	7.94E+06	3.76E+10	4.67E+05	3.14E+09	3.89E+04	4.48E+08	5.56E+03	2.24E+08	2.78E+03	1.60E+08	1.98E+03
7.00E+06	5.60E+11	6.94E+06	3.29E+10	4.08E+05	2.75E+09	3.40E+04	3.92E+08	4.86E+03	1.96E+08	2.43E+03	1.40E+08	1.74E+03
6.00E+06	4.80E+11	5.95E+06	2.82E+10	3.50E+05	2.35E+09	2.92E+04	3.36E+08	4.17E+03	1.68E+08	2.08E+03	1.20E+08	1.49E+03
5.00E+06	4.00E+11	4.96E+06	2.35E+10	2.92E+05	1.96E+09	2.43E+04	2.80E+08	3.47E+03	1.40E+08	1.74E+03	1.00E+08	1.24E+03
4.70E+06	3.76E+11	4.66E+06	2.21E+10	2.74E+05	1.84E+09	2.29E+04	2.63E+08	3.27E+03	1.32E+08	1.63E+03	9.40E+07	1.17E+03
4.40E+06	3.52E+11	4.37E+06	2.07E+10	2.57E+05	1.73E+09	2.14E+04	2.46E+08	3.06E+03	1.23E+08	1.53E+03	8.80E+07	1.09E+03
4.10E+06	3.28E+11	4.07E+06	1.93E+10	2.39E+05	1.61E+09	1.99E+04	2.30E+08	2.85E+03	1.15E+08	1.42E+03	8.20E+07	1.02E+03
3.80E+06	3.04E+11	3.77E+06	1.79E+10	2.22E+05	1.49E+09	1.85E+04	2.13E+08	2.64E+03	1.06E+08	1.32E+03	7.60E+07	9.43E+02
3.50E+06	2.80E+11	3.47E+06	1.65E+10	2.04E+05	1.37E+09	1.70E+04	1.96E+08	2.43E+03	9.80E+07	1.22E+03	7.00E+07	8.68E+02
3.20E+06	2.56E+11	3.17E+06	1.51E+10	1.87E+05	1.25E+09	1.56E+04	1.79E+08	2.22E+03	8.96E+07	1.11E+03	6.40E+07	7.94E+02
2.90E+06	2.32E+11	2.88E+06	1.36E+10	1.69E+05	1.14E+09	1.41E+04	1.62E+08	2.01E+03	8.12E+07	1.01E+03	5.80E+07	7.20E+02
2.60E+06	2.08E+11	2.58E+06	1.22E+10	1.52E+05	1.02E+09	1.26E+04	1.46E+08	1.81E+03	7.28E+07	9.03E+02	5.20E+07	6.45E+02
2.30E+06	1.84E+11	2.28E+06	1.08E+10	1.34E+05	9.02E+08	1.12E+04	1.29E+08	1.60E+03	6.44E+07	7.99E+02	4.60E+07	5.71E+02
2.00E+06	1.60E+11	1.98E+06	9.41E+09	1.17E+05	7.84E+08	9.73E+03	1.12E+08	1.39E+03	5.60E+07	6.95E+02	4.00E+07	4.96E+02
1.80E+06	1.44E+11	1.79E+06	8.47E+09	1.05E+05	7.06E+08	8.75E+03	1.01E+08	1.25E+03	5.04E+07	6.25E+02	3.60E+07	4.47E+02
1.60E+06	1.28E+11	1.59E+06	7.53E+09	9.34E+04	6.27E+08	7.78E+03	8.96E+07	1.11E+03	4.48E+07	5.56E+02	3.20E+07	3.97E+02
1.40E+06	1.12E+11	1.39E+06	6.59E+09	8.17E+04	5.49E+08	6.81E+03	7.84E+07	9.73E+02	3.92E+07	4.86E+02	2.80E+07	3.47E+02
1.20E+06	9.60E+10	1.19E+06	5.65E+09	7.00E+04	4.71E+08	5.84E+03	6.72E+07	8.34E+02	3.36E+07	4.17E+02	2.40E+07	2.98E+02
1.00E+06	8.00E+10	9.92E+05	4.71E+09	5.84E+04	3.92E+08	4.86E+03	5.60E+07	6.95E+02	2.80E+07	3.47E+02	2.00E+07	2.48E+02
9.00E+05	7.20E+10	8.93E+05	4.24E+09	5.25E+04	3.53E+08	4.38E+03	5.04E+07	6.25E+02	2.52E+07	3.13E+02	1.80E+07	2.23E+02

8.00E+05	6.40E+10	7.94E+05	3.76E+09	4.67E+04	3.14E+08	3.89E+03	4.48E+07	5.56E+02	2.24E+07	2.78E+02	1.60E+07	1.98E+02
7.00E+05	5.60E+10	6.94E+05	3.29E+09	4.08E+04	2.75E+08	3.40E+03	3.92E+07	4.86E+02	1.96E+07	2.43E+02	1.40E+07	1.74E+02
6.00E+05	4.80E+10	5.95E+05	2.82E+09	3.50E+04	2.35E+08	2.92E+03	3.36E+07	4.17E+02	1.68E+07	2.08E+02	1.20E+07	1.49E+02
5.00E+05	4.00E+10	4.96E+05	2.35E+09	2.92E+04	1.96E+08	2.43E+03	2.80E+07	3.47E+02	1.40E+07	1.74E+02	1.00E+07	1.24E+02
4.50E+05	3.60E+10	4.46E+05	2.12E+09	2.63E+04	1.76E+08	2.19E+03	2.52E+07	3.13E+02	1.26E+07	1.56E+02	9.00E+06	1.12E+02
4.00E+05	3.20E+10	3.97E+05	1.88E+09	2.33E+04	1.57E+08	1.95E+03	2.24E+07	2.78E+02	1.12E+07	1.39E+02	8.00E+06	9.92E+01
3.50E+05	2.80E+10	3.47E+05	1.65E+09	2.04E+04	1.37E+08	1.70E+03	1.96E+07	2.43E+02	9.80E+06	1.22E+02	7.00E+06	8.68E+01
3.00E+05	2.40E+10	2.98E+05	1.41E+09	1.75E+04	1.18E+08	1.46E+03	1.68E+07	2.08E+02	8.40E+06	1.04E+02	6.00E+06	7.44E+01
2.50E+05	2.00E+10	2.48E+05	1.18E+09	1.46E+04	9.80E+07	1.22E+03	1.40E+07	1.74E+02	7.00E+06	8.68E+01	5.00E+06	6.20E+01
2.00E+05	1.60E+10	1.98E+05	9.41E+08	1.17E+04	7.84E+07	9.73E+02	1.12E+07	1.39E+02	5.60E+06	6.95E+01	4.00E+06	4.96E+01
1.80E+05	1.44E+10	1.79E+05	8.47E+08	1.05E+04	7.06E+07	8.75E+02	1.01E+07	1.25E+02	5.04E+06	6.25E+01	3.60E+06	4.47E+01
1.60E+05	1.28E+10	1.59E+05	7.53E+08	9.34E+03	6.27E+07	7.78E+02	8.96E+06	1.11E+02	4.48E+06	5.56E+01	3.20E+06	3.97E+01
1.40E+05	1.12E+10	1.39E+05	6.59E+08	8.17E+03	5.49E+07	6.81E+02	7.84E+06	9.73E+01	3.92E+06	4.86E+01	2.80E+06	3.47E+01
1.20E+05	9.60E+09	1.19E+05	5.65E+08	7.00E+03	4.71E+07	5.84E+02	6.72E+06	8.34E+01	3.36E+06	4.17E+01	2.40E+06	2.98E+01
1.00E+05	8.00E+09	9.92E+04	4.71E+08	5.84E+03	3.92E+07	4.86E+02	5.60E+06	6.95E+01	2.80E+06	3.47E+01	2.00E+06	2.48E+01
9.00E+04	7.20E+09	8.93E+04	4.24E+08	5.25E+03	3.53E+07	4.38E+02	5.04E+06	6.25E+01	2.52E+06	3.13E+01	1.80E+06	2.23E+01
8.00E+04	6.40E+09	7.94E+04	3.76E+08	4.67E+03	3.14E+07	3.89E+02	4.48E+06	5.56E+01	2.24E+06	2.78E+01	1.60E+06	1.98E+01
7.00E+04	5.60E+09	6.94E+04	3.29E+08	4.08E+03	2.75E+07	3.40E+02	3.92E+06	4.86E+01	1.96E+06	2.43E+01	1.40E+06	1.74E+01
6.00E+04	4.80E+09	5.95E+04	2.82E+08	3.50E+03	2.35E+07	2.92E+02	3.36E+06	4.17E+01	1.68E+06	2.08E+01	1.20E+06	1.49E+01
5.00E+04	4.00E+09	4.96E+04	2.35E+08	2.92E+03	1.96E+07	2.43E+02	2.80E+06	3.47E+01	1.40E+06	1.74E+01	1.00E+06	1.24E+01
4.50E+04	3.60E+09	4.46E+04	2.12E+08	2.63E+03	1.76E+07	2.19E+02	2.52E+06	3.13E+01	1.26E+06	1.56E+01	9.00E+05	1.12E+01
4.00E+04	3.20E+09	3.97E+04	1.88E+08	2.33E+03	1.57E+07	1.95E+02	2.24E+06	2.78E+01	1.12E+06	1.39E+01	8.00E+05	9.92E+00
3.50E+04	2.80E+09	3.47E+04	1.65E+08	2.04E+03	1.37E+07	1.70E+02	1.96E+06	2.43E+01	9.80E+05	1.22E+01	7.00E+05	8.68E+00
3.00E+04	2.40E+09	2.98E+04	1.41E+08	1.75E+03	1.18E+07	1.46E+02	1.68E+06	2.08E+01	8.40E+05	1.04E+01	6.00E+05	7.44E+00
2.50E+04	2.00E+09	2.48E+04	1.18E+08	1.46E+03	9.80E+06	1.22E+02	1.40E+06	1.74E+01	7.00E+05	8.68E+00	5.00E+05	6.20E+00
2.00E+04	1.60E+09	1.98E+04	9.41E+07	1.17E+03	7.84E+06	9.73E+01	1.12E+06	1.39E+01	5.60E+05	6.95E+00	4.00E+05	4.96E+00
1.50E+04	1.20E+09	1.49E+04	7.06E+07	8.75E+02	5.88E+06	7.29E+01	8.40E+05	1.04E+01	4.20E+05	5.21E+00	3.00E+05	3.72E+00
1.00E+04	8.00E+08	9.92E+03	4.71E+07	5.84E+02	3.92E+06	4.86E+01	5.60E+05	6.95E+00	2.80E+05	3.47E+00	2.00E+05	2.48E+00
9.00E+03	7.20E+08	8.93E+03	4.24E+07	5.25E+02	3.53E+06	4.38E+01	5.04E+05	6.25E+00	2.52E+05	3.13E+00	1.80E+05	2.23E+00
8.00E+03	6.40E+08	7.94E+03	3.76E+07	4.67E+02	3.14E+06	3.89E+01	4.48E+05	5.56E+00	2.24E+05	2.78E+00	1.60E+05	1.98E+00
7.00E+03	5.60E+08	6.94E+03	3.29E+07	4.08E+02	2.75E+06	3.40E+01	3.92E+05	4.86E+00	1.96E+05	2.43E+00	1.40E+05	1.74E+00
6.00E+03	4.80E+08	5.95E+03	2.82E+07	3.50E+02	2.35E+06	2.92E+01	3.36E+05	4.17E+00	1.68E+05	2.08E+00	1.20E+05	1.49E+00
5.00E+03	4.00E+08	4.96E+03	2.35E+07	2.92E+02	1.96E+06	2.43E+01	2.80E+05	3.47E+00	1.40E+05	1.74E+00	1.00E+05	1.24E+00
4.00E+03	3.20E+08	3.97E+03	1.88E+07	2.33E+02	1.57E+06	1.95E+01	2.24E+05	2.78E+00	1.12E+05	1.39E+00	8.00E+04	9.92E-01
3.00E+03	2.40E+08	2.98E+03	1.41E+07	1.75E+02	1.18E+06	1.46E+01	1.68E+05	2.08E+00	8.40E+04	1.04E+00	6.00E+04	7.44E-01
2.00E+03	1.60E+08	1.98E+03	9.41E+06	1.17E+02	7.84E+05	9.73E+00	1.12E+05	1.39E+00	5.60E+04	6.95E-01	4.00E+04	4.96E-01
1.00E+03	8.00E+07	9.92E+02	4.71E+06	5.84E+01	3.92E+05	4.86E+00	5.60E+04	6.95E-01	2.80E+04	3.47E-01	2.00E+04	2.48E-01
9.00E+02	7.20E+07	8.93E+02	4.24E+06	5.25E+01	3.53E+05	4.38E+00	5.04E+04	6.25E-01	2.52E+04	3.13E-01	1.80E+04	2.23E-01
8.00E+02	6.40E+07	7.94E+02	3.76E+06	4.67E+01	3.14E+05	3.89E+00	4.48E+04	5.56E-01	2.24E+04	2.78E-01	1.60E+04	1.98E-01
7.00E+02	5.60E+07	6.94E+02	3.29E+06	4.08E+01	2.75E+05	3.40E+00	3.92E+04	4.86E-01	1.96E+04	2.43E-01	1.40E+04	1.74E-01
6.00E+02	4.80E+07	5.95E+02	2.82E+06	3.50E+01	2.35E+05	2.92E+00	3.36E+04	4.17E-01	1.68E+04	2.08E-01	1.20E+04	1.49E-01
5.00E+02	4.00E+07	4.96E+02	2.35E+06	2.92E+01	1.96E+05	2.43E+00	2.80E+04	3.47E-01	1.40E+04	1.74E-01	1.00E+04	1.24E-01
4.00E+02	3.20E+07	3.97E+02	1.88E+06	2.33E+01	1.57E+05	1.95E+00	2.24E+04	2.78E-01	1.12E+04	1.39E-01	8.00E+03	9.92E-02

3.00E+02	2.40E+07	2.98E+02	1.41E+06	1.75E+01	1.18E+05	1.46E+00	1.68E+04	2.08E-01	8.40E+03	1.04E-01	6.00E+03	7.44E-02
2.00E+02	1.60E+07	1.98E+02	9.41E+05	1.17E+01	7.84E+04	9.73E-01	1.12E+04	1.39E-01	5.60E+03	6.95E-02	4.00E+03	4.96E-02
1.00E+02	8.00E+06	9.92E+01	4.71E+05	5.84E+00	3.92E+04	4.86E-01	5.60E+03	6.95E-02	2.80E+03	3.47E-02	2.00E+03	2.48E-02
9.00E+01	7.20E+06	8.93E+01	4.24E+05	5.25E+00	3.53E+04	4.38E-01	5.04E+03	6.25E-02	2.52E+03	3.13E-02	1.80E+03	2.23E-02
8.00E+01	6.40E+06	7.94E+01	3.76E+05	4.67E+00	3.14E+04	3.89E-01	4.48E+03	5.56E-02	2.24E+03	2.78E-02	1.60E+03	1.98E-02
7.00E+01	5.60E+06	6.94E+01	3.29E+05	4.08E+00	2.75E+04	3.40E-01	3.92E+03	4.86E-02	1.96E+03	2.43E-02	1.40E+03	1.74E-02
6.00E+01	4.80E+06	5.95E+01	2.82E+05	3.50E+00	2.35E+04	2.92E-01	3.36E+03	4.17E-02	1.68E+03	2.08E-02	1.20E+03	1.49E-02
5.00E+01	4.00E+06	4.96E+01	2.35E+05	2.92E+00	1.96E+04	2.43E-01	2.80E+03	3.47E-02	1.40E+03	1.74E-02	1.00E+03	1.24E-02
4.00E+01	3.20E+06	3.97E+01	1.88E+05	2.33E+00	1.57E+04	1.95E-01	2.24E+03	2.78E-02	1.12E+03	1.39E-02	8.00E+02	9.92E-03
3.00E+01	2.40E+06	2.98E+01	1.41E+05	1.75E+00	1.18E+04	1.46E-01	1.68E+03	2.08E-02	8.40E+02	1.04E-02	6.00E+02	7.44E-03
2.00E+01	1.60E+06	1.98E+01	9.41E+04	1.17E+00	7.84E+03	9.73E-02	1.12E+03	1.39E-02	5.60E+02	6.95E-03	4.00E+02	4.96E-03
1.00E+01	8.00E+05	9.92E+00	4.71E+04	5.84E-01	3.92E+03	4.86E-02	5.60E+02	6.95E-03	2.80E+02	3.47E-03	2.00E+02	2.48E-03
9.00E+00	7.20E+05	8.93E+00	4.24E+04	5.25E-01	3.53E+03	4.38E-02	5.04E+02	6.25E-03	2.52E+02	3.13E-03	1.80E+02	2.23E-03
8.00E+00	6.40E+05	7.94E+00	3.76E+04	4.67E-01	3.14E+03	3.89E-02	4.48E+02	5.56E-03	2.24E+02	2.78E-03	1.60E+02	1.98E-03
7.00E+00	5.60E+05	6.94E+00	3.29E+04	4.08E-01	2.75E+03	3.40E-02	3.92E+02	4.86E-03	1.96E+02	2.43E-03	1.40E+02	1.74E-03
6.00E+00	4.80E+05	5.95E+00	2.82E+04	3.50E-01	2.35E+03	2.92E-02	3.36E+02	4.17E-03	1.68E+02	2.08E-03	1.20E+02	1.49E-03
5.00E+00	4.00E+05	4.96E+00	2.35E+04	2.92E-01	1.96E+03	2.43E-02	2.80E+02	3.47E-03	1.40E+02	1.74E-03	1.00E+02	1.24E-03

Above the RED line is Intermediate Level waste (i.e.>12000 Bq g^{-1} for beta-gamma solid waste)

Below the GREEN line may not be categorised as radioactive waste (i.e. <0.37 Bq g^{-1} for solid waste)

In between these two lines the radioactive material would most likely be categorised as Low Level Waste.

TABLE 5.2b. PREDICTED WASTE MEDIA ARISINGS FROM DECONTAMINATION USING SPONGE-JET BLASTING

Based on $1m^2$ surface area, and a $0.07\ m^3$ waste volume with ~85% free space.

Spent Media From Each Recycling Operation

Specify % Losses For Each Pass;

PASS 1 =	17	based on a 1 sq.m surface area
PASS 2 =	17	(Losses corrected upwards slightly to take account of a full media recycles)
PASS 3 =	17	
PASS 4 =	17	
PASS 5 =	17	
Total Loss =	76	
Mean Loss =	17	
Monitor conversion factor =	8	Where 100 microSieverts/hr is equivalent to 800Bq/sq.cm for conversion from RO2 to BP3 measurements
Total Sample Area =	10000	sq.cm Assumes a cube with six sides ~41 cm sq. (0.40825 m)
Mass of waste (g) =	80640	Assumes 0.07cu.metres of steel waste at 7.8te/cu.metre and 85% voidage = 80640g of waste
Initial Trial Media Volume =	25696	cu.cm Link to waste volume sheet(This assumes the worst case coverage see Chapter 4.1-recycling)
Mass of Media =	13618.88	g Based on the bulk mass of media being 530kg/cubic metre

Dose Rate	Start Activity	Specific Start	Media Vol	Waste Media	SpecP1 Media	Media Vol	Waste Media	SpecP2 Media	Media Vol	Waste Media	SpecP3 Media	Media Vol	Waste Media	SpecP4 Media	Media Vol	Waste Media	SpecP5 Media	Spec Act'y
(μSv/hr)	(Bq)	Act'y (Bq/g)	(cc) Pass1	Act'y (Bq)P1	Act'y (Bq/g)	(cc) Pass2	Act'y(Bq)P2	Act'y (Bq/g)	(cc) Pass 3	Act'y (Bq)P3	Act'y (Bq/g)	(cc) Pass 4	Act'y (Bq)P4	Act'y (Bq/g)	(cc) Pass 4	Act'y (Bq)P4	Act'y (Bq/g)	AllMedia (Bq/g)
1.00E+7	8.00E+11	9.92E+6	1.46E+3	7.53E+11	3.25E+8	2.91E+3	7.96E+11	1.72E+8	4.37E+3	7.99E+11	1.15E+8	5.82E+3	8.00E+11	8.64E+7	7.28E+3	8.00E+11	6.91E+7	5.87E+7
9.00E+6	7.20E+11	8.93E+6	1.46E+3	6.78E+11	2.93E+8	2.91E+3	7.16E+11	1.55E+8	4.37E+3	7.19E+11	1.04E+8	5.82E+3	7.20E+11	7.77E+7	7.28E+3	7.20E+11	6.22E+7	5.29E+7
8.00E+6	6.40E+11	7.94E+6	1.46E+3	6.02E+11	2.60E+8	2.91E+3	6.37E+11	1.38E+8	4.37E+3	6.40E+11	9.21E+7	5.82E+3	6.40E+11	6.91E+7	7.28E+3	6.40E+11	5.53E+7	4.70E+7
7.00E+6	5.60E+11	6.94E+6	1.46E+3	5.27E+11	2.28E+8	2.91E+3	5.57E+11	1.20E+8	4.37E+3	5.60E+11	8.06E+7	5.82E+3	5.60E+11	6.04E+7	7.28E+3	5.60E+11	4.84E+7	4.11E+7
6.00E+6	4.80E+11	5.95E+6	1.46E+3	4.52E+11	1.95E+8	2.91E+3	4.78E+11	1.03E+8	4.37E+3	4.80E+11	6.91E+7	5.82E+3	4.80E+11	5.18E+7	7.28E+3	4.80E+11	4.15E+7	3.52E+7
5.00E+6	4.00E+11	4.96E+6	1.46E+3	3.76E+11	1.63E+8	2.91E+3	3.98E+11	8.60E+7	4.37E+3	4.00E+11	5.75E+7	5.82E+3	4.00E+11	4.32E+7	7.28E+3	4.00E+11	3.45E+7	2.94E+7
4.70E+6	3.76E+11	4.66E+6	1.46E+3	3.54E+11	1.53E+8	2.91E+3	3.74E+11	8.08E+7	4.37E+3	3.76E+11	5.41E+7	5.82E+3	3.76E+11	4.06E+7	7.28E+3	3.76E+11	3.25E+7	2.76E+7
4.40E+6	3.52E+11	4.37E+6	1.46E+3	3.31E+11	1.43E+8	2.91E+3	3.50E+11	7.56E+7	4.37E+3	3.52E+11	5.06E+7	5.82E+3	3.52E+11	3.80E+7	7.28E+3	3.52E+11	3.04E+7	2.58E+7
4.10E+6	3.28E+11	4.07E+6	1.46E+3	3.09E+11	1.33E+8	2.91E+3	3.26E+11	7.05E+7	4.37E+3	3.28E+11	4.72E+7	5.82E+3	3.28E+11	3.54E+7	7.28E+3	3.28E+11	2.83E+7	2.41E+7
3.80E+6	3.04E+11	3.77E+6	1.46E+3	2.86E+11	1.24E+8	2.91E+3	3.03E+11	6.53E+7	4.37E+3	3.04E+11	4.37E+7	5.82E+3	3.04E+11	3.28E+7	7.28E+3	3.04E+11	2.63E+7	2.23E+7
3.50E+6	2.80E+11	3.47E+6	1.46E+3	2.64E+11	1.14E+8	2.91E+3	2.79E+11	6.02E+7	4.37E+3	2.80E+11	4.03E+7	5.82E+3	2.80E+11	3.02E+7	7.28E+3	2.80E+11	2.42E+7	2.06E+7
3.20E+6	2.56E+11	3.17E+6	1.46E+3	2.41E+11	1.04E+8	2.91E+3	2.55E+11	5.50E+7	4.37E+3	2.56E+11	3.68E+7	5.82E+3	2.56E+11	2.76E+7	7.28E+3	2.56E+11	2.21E+7	1.88E+7
2.90E+6	2.32E+11	2.88E+6	1.46E+3	2.18E+11	9.43E+7	2.91E+3	2.31E+11	4.99E+7	4.37E+3	2.32E+11	3.34E+7	5.82E+3	2.32E+11	2.50E+7	7.28E+3	2.32E+11	2.00E+7	1.70E+7
2.60E+6	2.08E+11	2.58E+6	1.46E+3	1.96E+11	8.46E+7	2.91E+3	2.07E+11	4.47E+7	4.37E+3	2.08E+11	2.99E+7	5.82E+3	2.08E+11	2.25E+7	7.28E+3	2.08E+11	1.80E+7	1.53E+7
2.30E+6	1.84E+11	2.28E+6	1.46E+3	1.73E+11	7.48E+7	2.91E+3	1.83E+11	3.95E+7	4.37E+3	1.84E+11	2.65E+7	5.82E+3	1.84E+11	1.99E+7	7.28E+3	1.84E+11	1.59E+7	1.35E+7
2.00E+6	1.60E+11	1.98E+6	1.46E+3	1.51E+11	6.50E+7	2.91E+3	1.59E+11	3.44E+7	4.37E+3	1.60E+11	2.30E+7	5.82E+3	1.60E+11	1.73E+7	7.28E+3	1.60E+11	1.38E+7	1.17E+7
1.80E+6	1.44E+11	1.79E+6	1.46E+3	1.36E+11	5.85E+7	2.91E+3	1.43E+11	3.09E+7	4.37E+3	1.44E+11	2.07E+7	5.82E+3	1.44E+11	1.55E+7	7.28E+3	1.44E+11	1.24E+7	1.06E+7
1.60E+6	1.28E+11	1.59E+6	1.46E+3	1.20E+11	5.20E+7	2.91E+3	1.27E+11	2.75E+7	4.37E+3	1.28E+11	1.84E+7	5.82E+3	1.28E+11	1.38E+7	7.28E+3	1.28E+11	1.11E+7	9.40E+6
1.40E+6	1.12E+11	1.39E+6	1.46E+3	1.05E+11	4.55E+7	2.91E+3	1.11E+11	2.41E+7	4.37E+3	1.12E+11	1.61E+7	5.82E+3	1.12E+11	1.21E+7	7.28E+3	1.12E+11	9.67E+6	8.22E+6
1.20E+6	9.60E+10	1.19E+6	1.46E+3	9.04E+10	3.90E+7	2.91E+3	9.55E+10	2.06E+7	4.37E+3	9.59E+10	1.38E+7	5.82E+3	9.60E+10	1.04E+7	7.28E+3	9.60E+10	8.29E+6	7.05E+6
1.00E+6	8.00E+10	9.92E+5	1.46E+3	7.53E+10	3.25E+7	2.91E+3	7.96E+10	1.72E+7	4.37E+3	7.99E+10	1.15E+7	5.82E+3	8.00E+10	8.64E+6	7.28E+3	8.00E+10	6.91E+6	5.87E+6

9.00E+5	7.20E+10	8.93E+5	1.46E+3	6.78E+10	2.93E+7	2.91E+3	7.16E+10	1.55E+7	4.37E+3	7.19E+10	1.04E+7	5.82E+3	7.20E+10	7.77E+6	7.28E+3	7.20E+10	6.22E+6	5.29E+6
8.00E+5	6.40E+10	7.94E+5	1.46E+3	6.02E+10	2.60E+7	2.91E+3	6.37E+10	1.38E+7	4.37E+3	6.40E+10	9.21E+6	5.82E+3	6.40E+10	6.91E+6	7.28E+3	6.40E+10	5.53E+6	4.70E+6
7.00E+5	5.60E+10	6.94E+5	1.46E+3	5.27E+10	2.28E+7	2.91E+3	5.57E+10	1.20E+7	4.37E+3	5.60E+10	8.06E+6	5.82E+3	5.60E+10	6.04E+6	7.28E+3	5.60E+10	4.84E+6	4.11E+6
6.00E+5	4.80E+10	5.95E+5	1.46E+3	4.52E+10	1.95E+7	2.91E+3	4.78E+10	1.03E+7	4.37E+3	4.80E+10	6.91E+6	5.82E+3	4.80E+10	5.18E+6	7.28E+3	4.80E+10	4.15E+6	3.52E+6
5.00E+5	4.00E+10	4.96E+5	1.46E+3	3.76E+10	1.63E+7	2.91E+3	3.98E+10	8.60E+6	4.37E+3	4.00E+10	5.75E+6	5.82E+3	4.00E+10	4.32E+6	7.28E+3	4.00E+10	3.45E+6	2.94E+6
4.50E+5	3.60E+10	4.46E+5	1.46E+3	3.39E+10	1.46E+7	2.91E+3	3.58E+10	7.74E+6	4.37E+3	3.60E+10	5.18E+6	5.82E+3	3.60E+10	3.89E+6	7.28E+3	3.60E+10	3.11E+6	2.64E+6
4.00E+5	3.20E+10	3.97E+5	1.46E+3	3.01E+10	1.30E+7	2.91E+3	3.18E+10	6.88E+6	4.37E+3	3.20E+10	4.60E+6	5.82E+3	3.20E+10	3.45E+6	7.28E+3	3.20E+10	2.76E+6	2.35E+6
3.50E+5	2.80E+10	3.47E+5	1.46E+3	2.64E+10	1.14E+7	2.91E+3	2.79E+10	6.02E+6	4.37E+3	2.80E+10	4.03E+6	5.82E+3	2.80E+10	3.02E+6	7.28E+3	2.80E+10	2.42E+6	2.06E+6
3.00E+5	2.40E+10	2.98E+5	1.46E+3	2.26E+10	9.76E+6	2.91E+3	2.39E+10	5.16E+6	4.37E+3	2.40E+10	3.45E+6	5.82E+3	2.40E+10	2.59E+6	7.28E+3	2.40E+10	2.07E+6	1.76E+6
2.50E+5	2.00E+10	2.48E+5	1.46E+3	1.88E+10	8.13E+6	2.91E+3	1.99E+10	4.30E+6	4.37E+3	2.00E+10	2.88E+6	5.82E+3	2.00E+10	2.16E+6	7.28E+3	2.00E+10	1.73E+6	1.47E+6
2.00E+5	1.60E+10	1.98E+5	1.46E+3	1.51E+10	6.50E+6	2.91E+3	1.59E+10	3.44E+6	4.37E+3	1.60E+10	2.30E+6	5.82E+3	1.60E+10	1.73E+6	7.28E+3	1.60E+10	1.38E+6	1.17E+6
1.80E+5	1.44E+10	1.79E+5	1.46E+3	1.36E+10	5.85E+6	2.91E+3	1.43E+10	3.09E+6	4.37E+3	1.44E+10	2.07E+6	5.82E+3	1.44E+10	1.55E+6	7.28E+3	1.44E+10	1.24E+6	1.06E+6
1.60E+5	1.28E+10	1.59E+5	1.46E+3	1.20E+10	5.20E+6	2.91E+3	1.27E+10	2.75E+6	4.37E+3	1.28E+10	1.84E+6	5.82E+3	1.28E+10	1.38E+6	7.28E+3	1.28E+10	1.11E+6	9.40E+5
1.40E+5	1.12E+10	1.39E+5	1.46E+3	1.05E+10	4.55E+6	2.91E+3	1.11E+10	2.41E+6	4.37E+3	1.12E+10	1.61E+6	5.82E+3	1.12E+10	1.21E+6	7.28E+3	1.12E+10	9.67E+5	8.22E+5
1.20E+5	9.60E+9	1.19E+5	1.46E+3	9.04E+9	3.90E+6	2.91E+3	9.55E+9	2.06E+6	4.37E+3	9.59E+9	1.38E+6	5.82E+3	9.60E+9	1.04E+6	7.28E+3	9.60E+9	8.29E+5	7.05E+5
1.00E+5	8.00E+9	9.92E+4	1.46E+3	7.53E+9	3.25E+6	2.91E+3	7.96E+9	1.72E+6	4.37E+3	7.99E+9	1.15E+6	5.82E+3	8.00E+9	8.64E+5	7.28E+3	8.00E+9	6.91E+5	5.87E+5
9.00E+4	7.20E+9	8.93E+4	1.46E+3	6.78E+9	2.93E+6	2.91E+3	7.16E+9	1.55E+6	4.37E+3	7.19E+9	1.04E+6	5.82E+3	7.20E+9	7.77E+5	7.28E+3	7.20E+9	6.22E+5	5.29E+5
8.00E+4	6.40E+9	7.94E+4	1.46E+3	6.02E+9	2.60E+6	2.91E+3	6.37E+9	1.38E+6	4.37E+3	6.40E+9	9.21E+5	5.82E+3	6.40E+9	6.91E+5	7.28E+3	6.40E+9	5.53E+5	4.70E+5
7.00E+4	5.60E+9	6.94E+4	1.46E+3	5.27E+9	2.28E+6	2.91E+3	5.57E+9	1.20E+6	4.37E+3	5.60E+9	8.06E+5	5.82E+3	5.60E+9	6.04E+5	7.28E+3	5.60E+9	4.84E+5	4.11E+5
6.00E+4	4.80E+9	5.95E+4	1.46E+3	4.52E+9	1.95E+6	2.91E+3	4.78E+9	1.03E+6	4.37E+3	4.80E+9	6.91E+5	5.82E+3	4.80E+9	5.18E+5	7.28E+3	4.80E+9	4.15E+5	3.52E+5
5.00E+4	4.00E+9	4.96E+4	1.46E+3	3.76E+9	1.63E+6	2.91E+3	3.98E+9	8.60E+5	4.37E+3	4.00E+9	5.75E+5	5.82E+3	4.00E+9	4.32E+5	7.28E+3	4.00E+9	3.45E+5	2.94E+5
4.50E+4	3.60E+9	4.46E+4	1.46E+3	3.39E+9	1.46E+6	2.91E+3	3.58E+9	7.74E+5	4.37E+3	3.60E+9	5.18E+5	5.82E+3	3.60E+9	3.89E+5	7.28E+3	3.60E+9	3.11E+5	2.64E+5
4.00E+4	3.20E+9	3.97E+4	1.46E+3	3.01E+9	1.30E+6	2.91E+3	3.18E+9	6.88E+5	4.37E+3	3.20E+9	4.60E+5	5.82E+3	3.20E+9	3.45E+5	7.28E+3	3.20E+9	2.76E+5	2.35E+5
3.50E+4	2.80E+9	3.47E+4	1.46E+3	2.64E+9	1.14E+6	2.91E+3	2.79E+9	6.02E+5	4.37E+3	2.80E+9	4.03E+5	5.82E+3	2.80E+9	3.02E+5	7.28E+3	2.80E+9	2.42E+5	2.06E+5
3.00E+4	2.40E+9	2.98E+4	1.46E+3	2.26E+9	9.76E+5	2.91E+3	2.39E+9	5.16E+5	4.37E+3	2.40E+9	3.45E+5	5.82E+3	2.40E+9	2.59E+5	7.28E+3	2.40E+9	2.07E+5	1.76E+5
2.50E+4	2.00E+9	2.48E+4	1.46E+3	1.88E+9	8.13E+5	2.91E+3	1.99E+9	4.30E+5	4.37E+3	2.00E+9	2.88E+5	5.82E+3	2.00E+9	2.16E+5	7.28E+3	2.00E+9	1.73E+5	1.47E+5
2.00E+4	1.60E+9	1.98E+4	1.46E+3	1.51E+9	6.50E+5	2.91E+3	1.59E+9	3.44E+5	4.37E+3	1.60E+9	2.30E+5	5.82E+3	1.60E+9	1.73E+5	7.28E+3	1.60E+9	1.38E+5	1.17E+5
1.50E+4	1.20E+9	1.49E+4	1.46E+3	1.13E+9	4.88E+5	2.91E+3	1.19E+9	2.58E+5	4.37E+3	1.20E+9	1.73E+5	5.82E+3	1.20E+9	1.30E+5	7.28E+3	1.20E+9	1.04E+5	8.81E+4
1.00E+4	8.00E+8	9.92E+3	1.46E+3	7.53E+8	3.25E+5	2.91E+3	7.96E+8	1.72E+5	4.37E+3	7.99E+8	1.15E+5	5.82E+3	8.00E+8	8.64E+4	7.28E+3	8.00E+8	6.91E+4	5.87E+4
9.00E+3	7.20E+8	8.93E+3	1.46E+3	6.78E+8	2.93E+5	2.91E+3	7.16E+8	1.55E+5	4.37E+3	7.19E+8	1.04E+5	5.82E+3	7.20E+8	7.77E+4	7.28E+3	7.20E+8	6.22E+4	5.29E+4
8.00E+3	6.40E+8	7.94E+3	1.46E+3	6.02E+8	2.60E+5	2.91E+3	6.37E+8	1.38E+5	4.37E+3	6.40E+8	9.21E+4	5.82E+3	6.40E+8	6.91E+4	7.28E+3	6.40E+8	5.53E+4	4.70E+4
7.00E+3	5.60E+8	6.94E+3	1.46E+3	5.27E+8	2.28E+5	2.91E+3	5.57E+8	1.20E+5	4.37E+3	5.60E+8	8.06E+4	5.82E+3	5.60E+8	6.04E+4	7.28E+3	5.60E+8	4.84E+4	4.11E+4
6.00E+3	4.80E+8	5.95E+3	1.46E+3	4.52E+8	1.95E+5	2.91E+3	4.78E+8	1.03E+5	4.37E+3	4.80E+8	6.91E+4	5.82E+3	4.80E+8	5.18E+4	7.28E+3	4.80E+8	4.15E+4	3.52E+4
5.00E+3	4.00E+8	4.96E+3	1.46E+3	3.76E+8	1.63E+5	2.91E+3	3.98E+8	8.60E+4	4.37E+3	4.00E+8	5.75E+4	5.82E+3	4.00E+8	4.32E+4	7.28E+3	4.00E+8	3.45E+4	2.94E+4
4.00E+3	3.20E+8	3.97E+3	1.46E+3	3.01E+8	1.30E+5	2.91E+3	3.18E+8	6.88E+4	4.37E+3	3.20E+8	4.60E+4	5.82E+3	3.20E+8	3.45E+4	7.28E+3	3.20E+8	2.76E+4	2.35E+4
3.00E+3	2.40E+8	2.98E+3	1.46E+3	2.26E+8	9.76E+4	2.91E+3	2.39E+8	5.16E+4	4.37E+3	2.40E+8	3.45E+4	5.82E+3	2.40E+8	2.59E+4	7.28E+3	2.40E+8	2.07E+4	1.76E+4
2.00E+3	1.60E+8	1.98E+3	1.46E+3	1.51E+8	6.50E+4	2.91E+3	1.59E+8	3.44E+4	4.37E+3	1.60E+8	2.30E+4	5.82E+3	1.60E+8	1.73E+4	7.28E+3	1.60E+8	1.38E+4	1.17E+4
1.00E+3	8.00E+7	9.92E+2	1.46E+3	7.53E+7	3.25E+4	2.91E+3	7.96E+7	1.72E+4	4.37E+3	7.99E+7	1.15E+4	5.82E+3	8.00E+7	8.64E+3	7.28E+3	8.00E+7	6.91E+3	5.87E+3
9.00E+2	7.20E+7	8.93E+2	1.46E+3	6.78E+7	2.93E+4	2.91E+3	7.16E+7	1.55E+4	4.37E+3	7.19E+7	1.04E+4	5.82E+3	7.20E+7	7.77E+3	7.28E+3	7.20E+7	6.22E+3	5.29E+3
8.00E+2	6.40E+7	7.94E+2	1.46E+3	6.02E+7	2.60E+4	2.91E+3	6.37E+7	1.38E+4	4.37E+3	6.40E+7	9.21E+3	5.82E+3	6.40E+7	6.91E+3	7.28E+3	6.40E+7	5.53E+3	4.70E+3
7.00E+2	5.60E+7	6.94E+2	1.46E+3	5.27E+7	2.28E+4	2.91E+3	5.57E+7	1.20E+4	4.37E+3	5.60E+7	8.06E+3	5.82E+3	5.60E+7	6.04E+3	7.28E+3	5.60E+7	4.84E+3	4.11E+3
6.00E+2	4.80E+7	5.95E+2	1.46E+3	4.52E+7	1.95E+4	2.91E+3	4.78E+7	1.03E+4	4.37E+3	4.80E+7	6.91E+3	5.82E+3	4.80E+7	5.18E+3	7.28E+3	4.80E+7	4.15E+3	3.52E+3
5.00E+2	4.00E+7	4.96E+2	1.46E+3	3.76E+7	1.63E+4	2.91E+3	3.98E+7	8.60E+3	4.37E+3	4.00E+7	5.75E+3	5.82E+3	4.00E+7	4.32E+3	7.28E+3	4.00E+7	3.45E+3	2.94E+3

4.00E+2	3.20E+7	3.97E+2	1.46E+3	3.01E+7	1.30E+4	2.91E+3	3.18E+7	6.88E+3	4.37E+3	3.20E+7	4.60E+3	5.82E+3	3.20E+7	3.45E+3	7.28E+3	3.20E+7	2.76E+3	2.35E+3
3.00E+2	2.40E+7	2.98E+2	1.46E+3	2.26E+7	9.76E+3	2.91E+3	2.39E+7	5.16E+3	4.37E+3	2.40E+7	3.45E+3	5.82E+3	2.40E+7	2.59E+3	7.28E+3	2.40E+7	2.07E+3	1.76E+3
2.00E+2	1.60E+7	1.98E+2	1.46E+3	1.51E+7	6.50E+3	2.91E+3	1.59E+7	3.44E+3	4.37E+3	1.60E+7	2.30E+3	5.82E+3	1.60E+7	1.73E+3	7.28E+3	1.60E+7	1.38E+3	1.17E+3
1.00E+2	8.00E+6	9.92E+1	1.46E+3	7.53E+6	3.25E+3	2.91E+3	7.96E+6	1.72E+3	4.37E+3	7.99E+6	1.15E+3	5.82E+3	8.00E+6	8.64E+2	7.28E+3	8.00E+6	6.91E+2	5.87E+2
9.00E+1	7.20E+6	8.93E+1	1.46E+3	6.78E+6	2.93E+3	2.91E+3	7.16E+6	1.55E+3	4.37E+3	7.19E+6	1.04E+3	5.82E+3	7.20E+6	7.77E+2	7.28E+3	7.20E+6	6.22E+2	5.29E+2
8.00E+1	6.40E+6	7.94E+1	1.46E+3	6.02E+6	2.60E+3	2.91E+3	6.37E+6	1.38E+3	4.37E+3	6.40E+6	9.21E+2	5.82E+3	6.40E+6	6.91E+2	7.28E+3	6.40E+6	5.53E+2	4.70E+2
7.00E+1	5.60E+6	6.94E+1	1.46E+3	5.27E+6	2.28E+3	2.91E+3	5.57E+6	1.20E+3	4.37E+3	5.60E+6	8.06E+2	5.82E+3	5.60E+6	6.04E+2	7.28E+3	5.60E+6	4.84E+2	4.11E+2
6.00E+1	4.80E+6	5.95E+1	1.46E+3	4.52E+6	1.95E+3	2.91E+3	4.78E+6	1.03E+3	4.37E+3	4.80E+6	6.91E+2	5.82E+3	4.80E+6	5.18E+2	7.28E+3	4.80E+6	4.15E+2	3.52E+2
5.00E+1	4.00E+6	4.96E+1	1.46E+3	3.76E+6	1.63E+3	2.91E+3	3.98E+6	8.60E+2	4.37E+3	4.00E+6	5.75E+2	5.82E+3	4.00E+6	4.32E+2	7.28E+3	4.00E+6	3.45E+2	2.94E+2
4.00E+1	3.20E+6	3.97E+1	1.46E+3	3.01E+6	1.30E+3	2.91E+3	3.18E+6	6.88E+2	4.37E+3	3.20E+6	4.60E+2	5.82E+3	3.20E+6	3.45E+2	7.28E+3	3.20E+6	2.76E+2	2.35E+2
3.00E+1	2.40E+6	2.98E+1	1.46E+3	2.26E+6	9.76E+2	2.91E+3	2.39E+6	5.16E+2	4.37E+3	2.40E+6	3.45E+2	5.82E+3	2.40E+6	2.59E+2	7.28E+3	2.40E+6	2.07E+2	1.76E+2
2.00E+1	1.60E+6	1.98E+1	1.46E+3	1.51E+6	6.50E+2	2.91E+3	1.59E+6	3.44E+2	4.37E+3	1.60E+6	2.30E+2	5.82E+3	1.60E+6	1.73E+2	7.28E+3	1.60E+6	1.38E+2	1.17E+2
1.00E+1	8.00E+5	9.92E+0	1.46E+3	7.53E+5	3.25E+2	2.91E+3	7.96E+5	1.72E+2	4.37E+3	7.99E+5	1.15E+2	5.82E+3	8.00E+5	8.64E+1	7.28E+3	8.00E+5	6.91E+1	5.87E+1
9.00E+0	7.20E+5	8.93E+0	1.46E+3	6.78E+5	2.93E+2	2.91E+3	7.16E+5	1.55E+2	4.37E+3	7.19E+5	1.04E+2	5.82E+3	7.20E+5	7.77E+1	7.28E+3	7.20E+5	6.22E+1	5.29E+1
8.00E+0	6.40E+5	7.94E+0	1.46E+3	6.02E+5	2.60E+2	2.91E+3	6.37E+5	1.38E+2	4.37E+3	6.40E+5	9.21E+1	5.82E+3	6.40E+5	6.91E+1	7.28E+3	6.40E+5	5.53E+1	4.70E+1
7.00E+0	5.60E+5	6.94E+0	1.46E+3	5.27E+5	2.28E+2	2.91E+3	5.57E+5	1.20E+2	4.37E+3	5.60E+5	8.06E+1	5.82E+3	5.60E+5	6.04E+1	7.28E+3	5.60E+5	4.84E+1	4.11E+1
6.00E+0	4.80E+5	5.95E+0	1.46E+3	4.52E+5	1.95E+2	2.91E+3	4.78E+5	1.03E+2	4.37E+3	4.80E+5	6.91E+1	5.82E+3	4.80E+5	5.18E+1	7.28E+3	4.80E+5	4.15E+1	3.52E+1
5.00E+0	4.00E+5	4.96E+0	1.46E+3	3.76E+5	1.63E+2	2.91E+3	3.98E+5	8.60E+1	4.37E+3	4.00E+5	5.75E+1	5.82E+3	4.00E+5	4.32E+1	7.28E+3	4.00E+5	3.45E+1	2.94E+1

Above the RED line the waste media will be disposed of as Intermediate Level beta-gamma solid waste, and below the line it will need to be disposed of as LLW

5.3 ENVIRONMENTAL IMPACT

An anticipated in-cave decontamination system will need to process ILW/LLW in a production environment within the WAHF, and the case for introducing it will require an environmental impact assessment (EIA). The benefits of the process in terms of disposals to land/interim storage have already been covered. There may be environmental impacts through aerial discharges from a Sponge-jet decontamination system. These impacts are considered as follows.

The higher activity trials removed just over 2 MBq of radioactivity, if the system is developed into a routine process for in-cave decontamination of waste it will be required to remove many times this amount of contamination. For the purpose of this study, it has been cautiously assumed that ten times the trial activity will be cleaned per week (20 MBq) and these operations will continue for 50 weeks a year.

During higher activity trials the system was in operation for no more than 20 minutes which at maximum system operations (12 m^3 min^{-1}) means ~240 m^3 of air was ventilated to atmosphere. Assuming waste processing is proportional, the air volume discharged per year could be 120000 m^3. This discharge could effectively mix with the building extract volume flow in the header duct prior to discharge, generating a further dilution of >20 times.

If the system processes ILW and removes 1 GBq of radioactivity per year, it would be abated in turn by the gravity settler, cyclone, primary and secondary HEPA filtration, and finally the building main filter banks. The trials have shown that a large proportion of the

contamination removed can be accounted for within the system (~80% see Table 4.3d). HEPA filters are designed to be 99.99% efficient and filter testing often demonstrates Dfs in excess of 10^2, so it unlikely that significant levels of radioactivity will escape to the environment.

Using the Environment Agency spreadsheets generated from the joint project with English Nature (see Section 2.2) [52] to assess the impacts of the radioactive discharges from the Sponge-jet process as configured for in-cave ILW decontamination, will give some indication of whether this aspect of the process is of concern. Figure 5.3a presents histograms describing the possible impacts on various generic classes of flora and fauna, various discharge scenarios. The input data is based on the main radionuclides from the WAHF fingerprint for ILW/LLW [68, 69], where ^{137}Cs, ^{90}Sr and ^{241}Pu account for more than two thirds (~69%) of the activity present within the contamination. The EIA assessment spreadsheets only consider a limited range of isotopes and sometimes it is necessary to choose surrogate radionuclides for the assessment under consideration. Fortunately in this case the EIA sheets have ^{137}Cs and ^{90}Sr, but Pu is represented by ^{239}Pu and will therefore act as a surrogate for ^{241}Pu. These three radionuclides were increased proportionally to account for the total contamination activity giving 0.672 GBq of ^{137}Cs, 0.17 GBq of ^{90}Sr, and 0.158 GBq of ^{139}Pu. Concentrations are input to the spreadsheets so that dose uptake to generic flora and fauna are calculated. Consideration of the pathways for uptake of the radionuclides in plants and animals, specific interactions of certain wildlife with specific types of radionuclide (habitats), behaviour of radionuclides in soil, sediment and water, and the relative biological effectiveness of radionuclides for different biota are all taken in to account in generating absorbed dose uptake. The

equations used to calculate dose in the terrestrial ecosystem can be summarised as follows;

$$(\text{Soil conc.})_{nuclide} = (\text{Air conc.})_{nuclide} \times CF_{soil\ nuclide} \quad \text{(for } ^{3}H, ^{14}C \text{ and } ^{35}S)$$

$$(\text{Soil conc.})_{nuclide} = (\text{Soil conc. (dry)})_{nuclide} \times (\text{solids fraction}) \quad \text{(for other nuclides)}$$

$$(\text{Internal dose})_{nuclide,\ organism} = (\text{Air conc.})_{nuclide} \times CF_{nuc,org'm} \times DPUC_{internal,nuclide,\ org'm}$$
$(\text{Internal dose})_{nuclide}$ (for ^{3}H, ^{14}C and ^{35}S)

$$(\text{Internal dose})_{nuclide,\ organism} = (\text{Soil conc.})_{nuclide} \times CF_{nuc,org'm} \times DPUC_{internal,nuclide,\ org'm}$$
(for other nuclides)

$$(\text{External dose})_{nuclide,\ org'm} = DPUC_{external,\ nuclide,\ org'm} \times$$

$$[(\text{Soil conc})_{nuclide} \times ((fsoil_{org'm} + fsoilsur_{org'm}/2) + fair_{org'm} + (\text{reduction factor})_{rad'n\ type})]$$

Where:

Air concentrations for ^{3}H, ^{14}C and ^{35}S, and for other nuclides the input values are in Bq kg^{-1} dry weight;

Concentration factors for ^{3}H, ^{14}C and ^{35}S are as Bq kg^{-1} (fresh weight) of soil or organism per Bq m^{-3} in air, and for other nuclides are as Bq kg^{-1} (fresh weight) of organism per Bq kg^{-1} (dry weight) of soil;

(solids fraction) is the fractional dry solids content of fresh soil;

fsoil is the fraction of time the organism spends buried in, or burrowing into soil;

fsoilsur is the fraction of time the organism spends on the ground surface;

fair is the fraction of time the organism spends above the ground surface, flying or roosting etc.;

(reduction factor) is a factor, dependent on radiation type, by which the radiation dose rate above the ground surface lower than that within the soil itself. The default values set for this factor are zero for α and low energy β radiation, and 0.25 for high energy β radiation and γ rays.

Initially the discharge was modelled to include a number of pessimisms. Firstly only 50% of the contamination (and not 80% as in the trials) is retained by the medium and Sponge-jet management system. Secondly only a cautious Df of 10 is considered for the HEPA filtration (despite there being three filters in series). This leads to annual discharge of 0.05 GBq within 120000 m^3 (no account taken for the additional dilution from the building extract volume), and an aerial discharge concentration of ~417 Bq m^{-3}. It is pessimistically assumed that this concentration at discharge (Bq m^{-3}) accumulates in similar concentrations within the soil (Bq kg^{-1}) in the local environment. If the impacts challenge the UNSCEAR reference levels of 40 μGy hr^{-1} for terrestrial animal populations, and 400 μGy hr^{1} for terrestrial plant populations. These are considered to be chronic absorbed dose rates below which it unlikely that there will be any significant effects.

Figure 5b.1 shows how the impacts on various classes of biota if the discharges lead to concentration build up in the soil similar to the discharge concentration. Clearly the impacts to biota, even when incorporating all the pessimisms described previously are a long way from challenging the UNSCEAR reference levels for plant or animal populations. The dose uptake to animal populations from an annual discharge of 50 MBq is unlikely to exceed 1.5% of the 40 μGy reference level. Impacts to plant populations are less than 1% of the reference level. Plants appear to be impacted by the Pu more than the other nuclides, while there are varying impacts to animals depending on their behaviour relative to the nuclides interaction with the environment.

Figure 5.3b shows the impacts on biota approaching the reference levels when a discharge of ~3.3 GBq is considered. In fact a discharge of 4 GBq would be required in this

scenario before soil concentrations would potentially reach levels that may impact noticeably on animal populations. This would represent the decontamination of ILW where by ~80 GBq of contamination might have been removed.

Based on the Tables 5b. 1-4 the removal of 80 GBq of radioactivity could equate to processing between ~8 m^3 and ~15000 m^3 of LLW, leading to substantial savings in waste disposal costs. Furthermore, 80 GBq yr^{-1} could equate to processing up to 5 m^3 of ILW per year. In addition the deferral of tool and equipment disposal by virtue of refurbishment and reuse across the industry could generate further savings.

A key uncertainty with the performance of the system in terms of abatement is that the cyclone separator is designed to remove medium particles with the bulk density of the foam. That is to mean the average density of the particle with polyurethane and grit contained. Much of the contamination will be from particles of much higher density. For a given particle size the cyclone should be more efficient for more dense materials, and should be equally efficient for particle sizes that are actually smaller than the design criteria. This area of study needs further investigation to establish more closely the system operating envelope and what specifically are the likely airborne impacts.

FIGURE 5.3a. SUMMARY OF DOSE UPTAKE TO GENERAL BIOTA GROUPS FROM ASSUMED AERIAL DISCHARGES

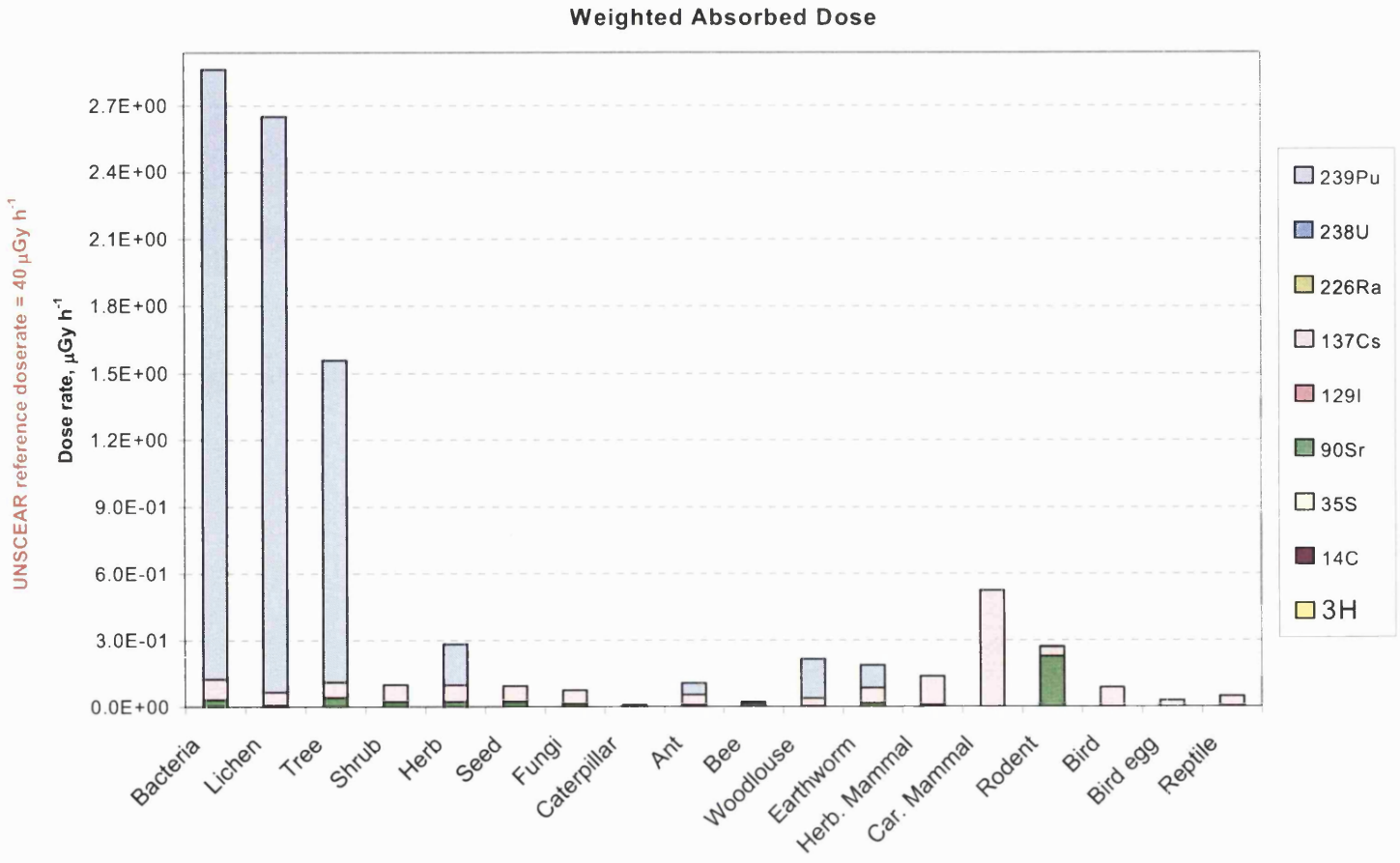
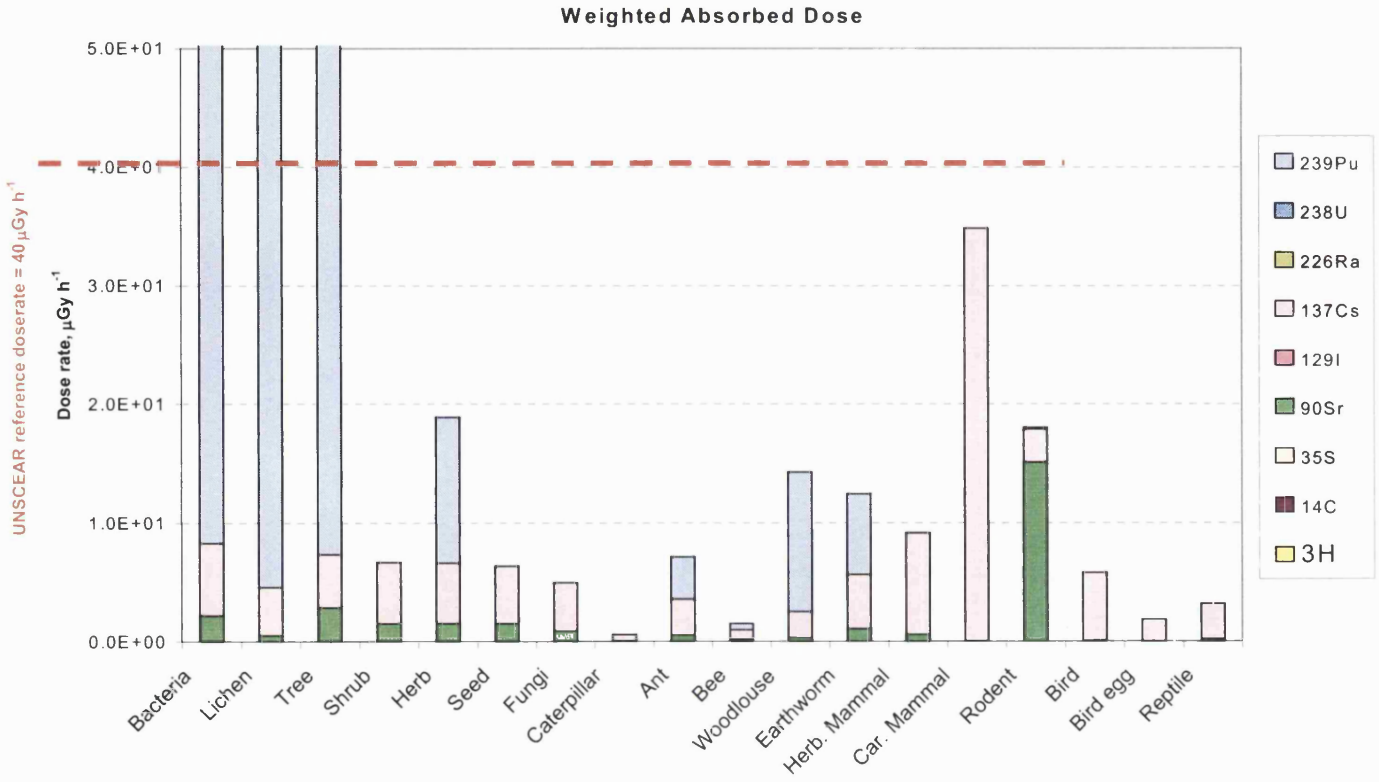


FIGURE 5.3b. DOSE UPTAKE APPROACHING REFERENCE LEVELS TO BIOTA FROM AERIAL DISCHARGES



5.4 OPPORTUNITIES FOR FURTHER WORK

In the time available the practical work reported here was as far as the project could be taken up to the end of 1999, and had the work been able to continue some areas of work may have been studied further. Continued decontamination trials in the enclosure at the actual system design flow rates would provide more confidence that the system works effectively, and contamination transfer rates can be confirmed.

Modifications need to be made to the medium volume reduction rig to enable inactive optimisation (both block size and shape and fusion temperatures) trials to be undertaken prior to active trials. All round and uniform heating (e.g. belt heaters) would help to ensure that the waste block would be consistently fused throughout its surface. This would help to assist remote handle for disposal without break up of the block and consequent spread of contamination.

Pneumatic systems need to be developed to enable spent or reusable medium to be 'hoovered' from one place to another e.g. from the gravity settler collection bin to the blast hopper or the waste volume reduction rig, and the cyclone collection bin to the waste volume reduction rig.

Further work could be directed at developing the process for other nuclear industry specific applications other than waste cleaning. The process has already been successfully applied for worker dose minimisation, where Butter et al [102] conducted a limited study into the process to support steam generator pipe end decontamination during boiler replacement [103]. During this work the author demonstrated that variants in the

medium available from Sponge-jet could be used to remove particularly tenacious magnetite coatings on reactor pressure vessel components, without damaging the underlying sub-strate. This would again minimise dose to operators who subsequently maintain such equipment. The process could be used in other practical situations within the nuclear industry, and or other hostile environments such as when dealing with toxic materials such as beryllium.

Future work could be directed at developing a nuclear industry specific medium focusing on medium life extend-ability. While polyether based polyurethanes provide foams with good load bearing properties, and tensile strength, polyester based polyurethane foams absorb more energy, have greater impact strength and better wear resistance [104]. Which combinations of Polyurethane and abrasive provide the best durability and therefore longevity is of particular interest for use in the nuclear industry. Studies could be undertaken into the medium life expectancy, which could consider mathematical modelling (tensor) of the complex stresses imposed on the sponge particles during impacts. The foam structure itself could be developed, where alternative foam might be more durable under the impact conditions. One potentialcandidate for development could be Chiral foam [105, 106] where the honeycomb exhibits a Poisson ratio that is negative, where re-entrant structures expand laterally as they are stretched. These open celled foams with negative Poison's ratio have been found to be more resilient than conventional foams[106]. The grit materials, and the bonding mechanism of grit to sponge medium may be improved such that it breaks up less readily and can be retained (improved endurance) by the foam for more recycles.

Further studies (e.g., evolved gas analysis) could be made into the expected breakdown of the polymer during prolonged periods of storage in the close proximity to alpha, beta and gamma radiation. The mechanisms that are involved in the adhesive bonding of the foam (and a wider range of plastics) in to more dense blocks needs to be understood in order to obtain an optimised solution for any future disposal process. Although the limited work undertaken here suggests that the medium will, within a limited number of years, breakdown into carbon and contamination dust as the radiation breaks down the molecular structure of the polyurethane material. It may be necessary therefore to effect further conditioning of this waste form following interim storage and prior to ultimate disposal in a repository i.e. immobilisation of the particulate in grout or chemical treatment [107].

Finally further abatement systems could be considered and evaluated to provide more reassurance of the environmental and economic benefit of the process. A possible addition considered for the ILW trials was the use of a recirculatory fluid scrubber [108].

CHAPTER 6. CONCLUDING REMARKS

1. The Sponge-jet blasting system has been successfully studied and trials conducted to investigate whether it would be feasible to use as a nuclear waste decontamination technology. Unique test rigs have been developed proving that a full-scale system could be designed for integration within the WAHF to enhance the existing waste management arrangements for both LLW and ILW. The results of this research work demonstrate that dry decontamination using Sponge-jet can clean specific wastes safely, commercially and in an environmentally friendly manner.

2. The conclusion of some studies has highlighted several areas which might be explored further such as; the analysis of evolved gas from polyurethane under radiation conditions; the nature of the medium bonding and its potential to stay bonded during storage and handling; and contamination transfer studies through the gravity settler and cyclone to confirm the integrity, and operational boundary of the medium management and abatement system.

3. Predictive models have been presented, based on the trial data gained from this work. It is anticipated that these models could be refined as more data is gained from further decontamination trials, to provide a waste management tool that would feed into the decision making process when considering the best practical means for dealing with future solid nuclear waste arising. This will be of particular application during the decommissioning of UK nuclear liabilities over the next decade or so.

4. An outline design proposal has been submitted for the construction of a permanent Low Level Waste decontamination system in the cave roof area of the Windscale Active Handling Facilities. The feasibility of an ILW system for use in the WAHF caves has been shown to be viable, subject to further design and development work.

5. A system of waste deployment, blast direction, medium containment, recycling, volume reduction and disposal has been developed to a stage where there is raised confidence of integrating all these waste management aspects. With further refinement this system could be developed into an integrated waste management process for the Windscale Active Handling Facilities.

6. Areas of further work have been proposed which would enhance this technology and provide additional confidence in the application of the Sponge-jet process as a nuclear waste management tool. These areas can be summarised as follows:

    - nuclear waste specific medium development
    - further waste medium characterisation for disposal
    - waste medium cleaning or treatment
    - develop the waste assessment and monitoring tools and protocols.

7. Papers are proposed for specific professional journals which will detail, develop and discuss relevant aspects of this work such as safety and environmental performance, production capacity and commercial benefits, further potential adaptations of the process as solutions for other specific nuclear problems, as well as the technical challenges to further enhance the process performance. Journals that may be receptive to such articles include Nuclear Future (the journal of the British Nuclear

Energy Society (BNES)), the Journal of Nuclear Materials, Materials World (the journal of the Institute of Materials, Minerals and Mining (IMMM)), the Nuclear Engineer (the journal of the Institution of Nuclear Engineers (INucE)), and the journal of Radiological Protection (the journal of the Society of Radiological Protection 9SRP)).

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